NUSC TM 831177

Naval Underwater Systems Center
New London Laboratory
New London, CT 06320

Technical Memorandum

Range Error Estimates Due To Depth and Bottom Slope

Date: 30 Nov 1983

Prepared by:
J. Matthew Tattersall
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General Engineer, 3331

DEPARTMENT OF THE NAVY
NAVAL UNDERWATER SYSTEMS CENTER
NEWPORT, RI ~~XXXXX~~ 02841

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New London, CT 06320

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Subj: NUSC Technical Memorandum; forwarding of

Encl: (1) J. Matthew Tattersall, "Range Error Estimates Due to Depth and Bottom Slope", NUSC TM No. 831177, 30 Nov 1983.

1. The Environmental Acoustic (EVA) Support for Shipboard Sonar and Weapons Block Program consists of four tasks. As a part of the first task (Broadband Acoustic Field Considerations for Combat System Design and Performance Evaluation), a study has been conducted at NUSC to investigate range estimation errors due to insufficient or erroneous bathymetric data. This work has shown that D/E ranging utilizing the first bottom bounce requires accurate knowledge of the bottom topography (i.e., depth and bottom slope) for viable range solutions. For example, in an isovelocity ocean, given a D/E angle of 20°, the bottom depth must be known within 90 fathoms to obtain a range error less than 1 kyd. This result is independent of the actual bottom depth.

2. Enclosure (1), documenting the results of this study, is forwarded for your interest and retention.

3. Any questions concerning this enclosure should be directed to Mr. Matt Tattersall, Code 3331 at (203) 447-5771.

T. E. Bateman
for L. FREEMAN
By direction

Range Error Estimates Due to
Depth and Bottom Slope
J. Matthew Tattersall, 3331
TM No. 831177
30 November 1983
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Technical Memorandum

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General Engineer, 3331

PREFACE

This report was prepared under NUSC Project No. A65000, EVA Support for Shipboard Sonar (U), Principal Investigator, B. F. Cole (Code 33A). The sponsoring activity is the Naval Sea Systems Command, C. D. Smith (NAVSEA 63R) Director. Funding is provided under Program Element No. 62759N, F. R. Romano, (NAVSEA 63R3) Manager. This effort was performed under Subproject SF 59-552A and coordinated with other Navy Subprojects through Dr. R. W. Farwell (NAVSEA 63R3).

ABSTRACT

Errors in range estimation by a single bottom bounce path are examined for several bottom geometries. The range error due to an incorrect water depth is examined, and it is shown that for horizontal bottom planes, the range error as a function of depth error is independent of the absolute water depth. Range errors associated with two bottom models with non-horizontal bounce point planes are examined. The range errors are studied as functions of depression angle, water depth, bottom slope, and cross slope angle. Computer programs have been written which calculate the range errors and the results are presented as contour plots. The results show the importance of accurate bathymetry for range estimation.

Range Estimation and Assumptions

Consider a bottom bounce sonar system as shown in figure 1, in which range to a near surface target is estimated using the water depth (d) and the depression angle (β).

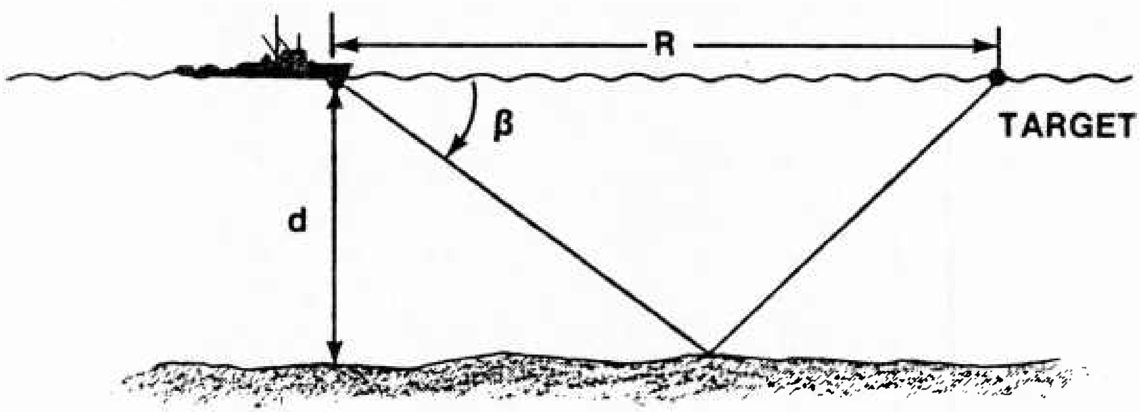


Figure 1.

If the depth at the bounce point is equal to d and the local plane at the bounce point is horizontal, then the range may be calculated by

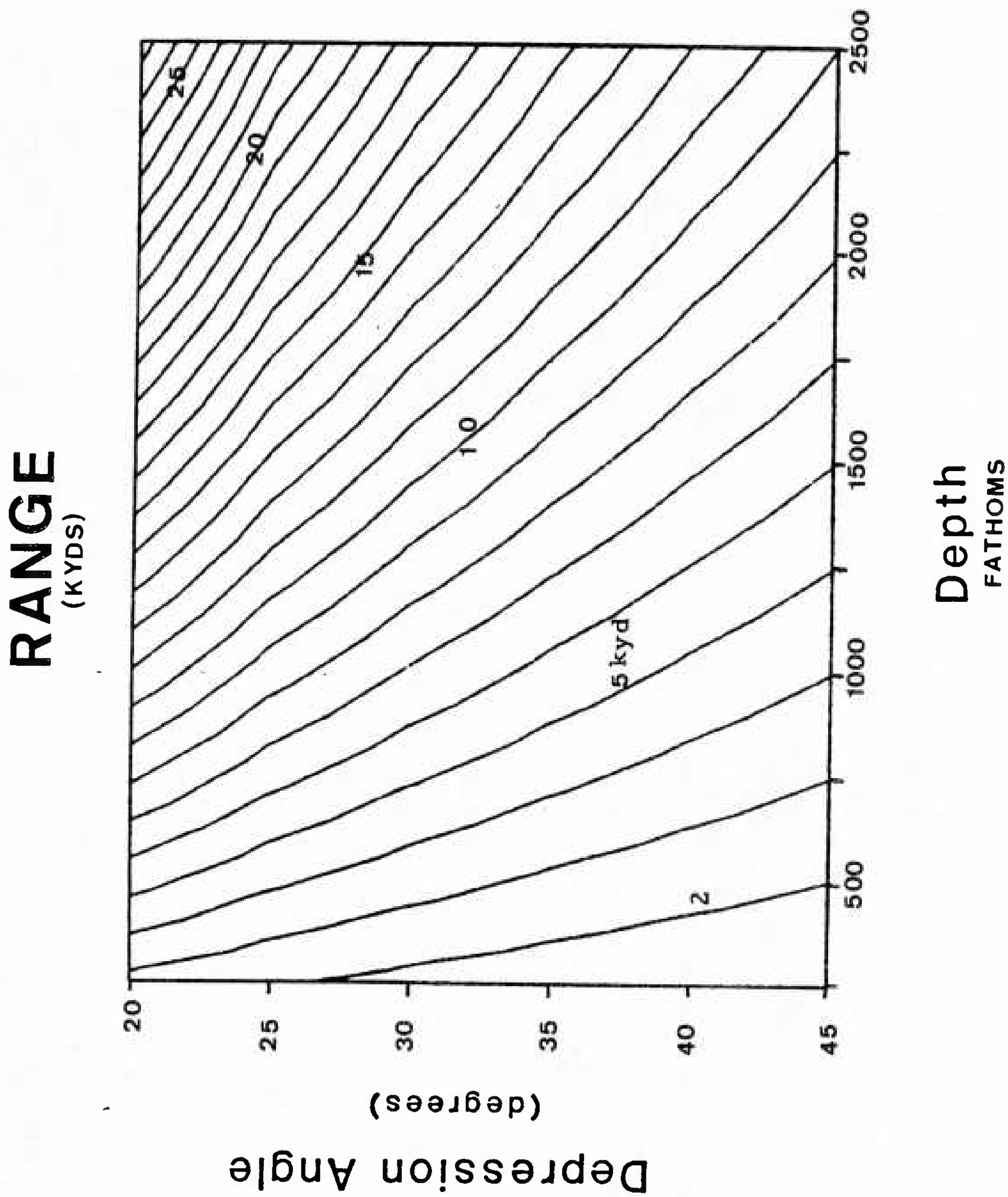
$$R = 2d/\tan\beta \tag{1}$$

This also assumes straight line propagation, i.e., an isovelocity ocean. Figure 2 gives range values for some typical depths and depression angles. The ranges for these cases extend from 1 to 27 kiloyards. For the remainder of this paper, the range given by equation (1) will be referred to as the apparent range.

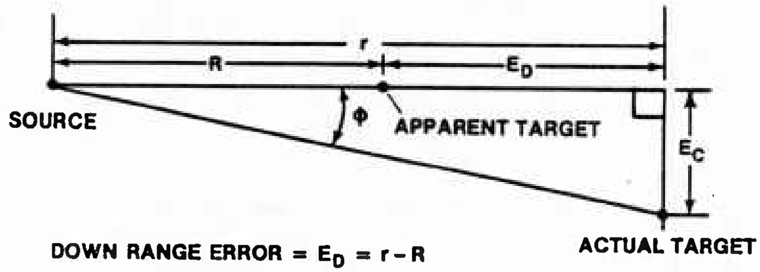
Error Definitions

Given conditions other than the above, e.g., a sloping bottom or an incorrect water depth, the range given by equation (1) will be erroneous. In general the range error has two components, a down range and a cross range error. A bearing or angular error can also be defined. Figure 3 shows the geometry defining the errors in this technical memorandum. Note that a negative range error means the target is actually closer than the apparent location and a negative cross range error indicates that the target is actually to the left of where the apparent target is located.

Figure 2.


RANGE
(KYDS)
Depth
FATHOMS
Depression Angle
(degrees)
20
25
30
35
40
45
500
1000
1500
2000
2500
2
5 kyd
10
15
20
25

GEOMETRY OF RANGE ERROR



DOWN RANGE ERROR = $E_D = r - R$

CROSS RANGE ERROR = E_C

BEARING ERROR = $\phi = \tan^{-1} \frac{E_C}{E_D + R}$

Figure 3.

Depth Difference Error

As a first step in this analysis, the assumption that the depth at the bounce point is equal to the measured water depth at the ship will be considered. Any depth difference (DD) that is not accounted for will cause an error in the range estimate. These depth differences can be caused by an incorrect measurement of depth, e. g., failing to correct charted values for the true sound velocity, interpolating from an undersampled chart or failing to account for variations in the local bathymetry (see figure 4).

RANGE ERROR CAUSED BY DEPTH ERROR

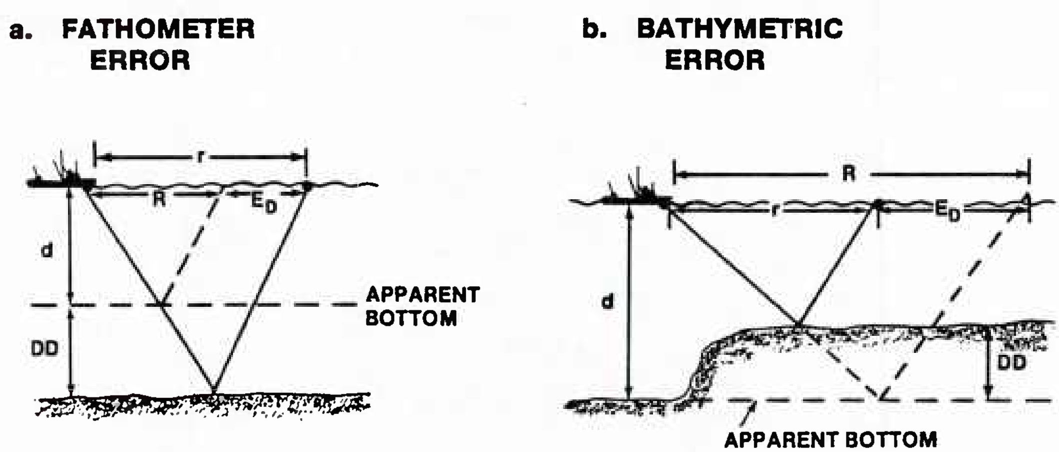
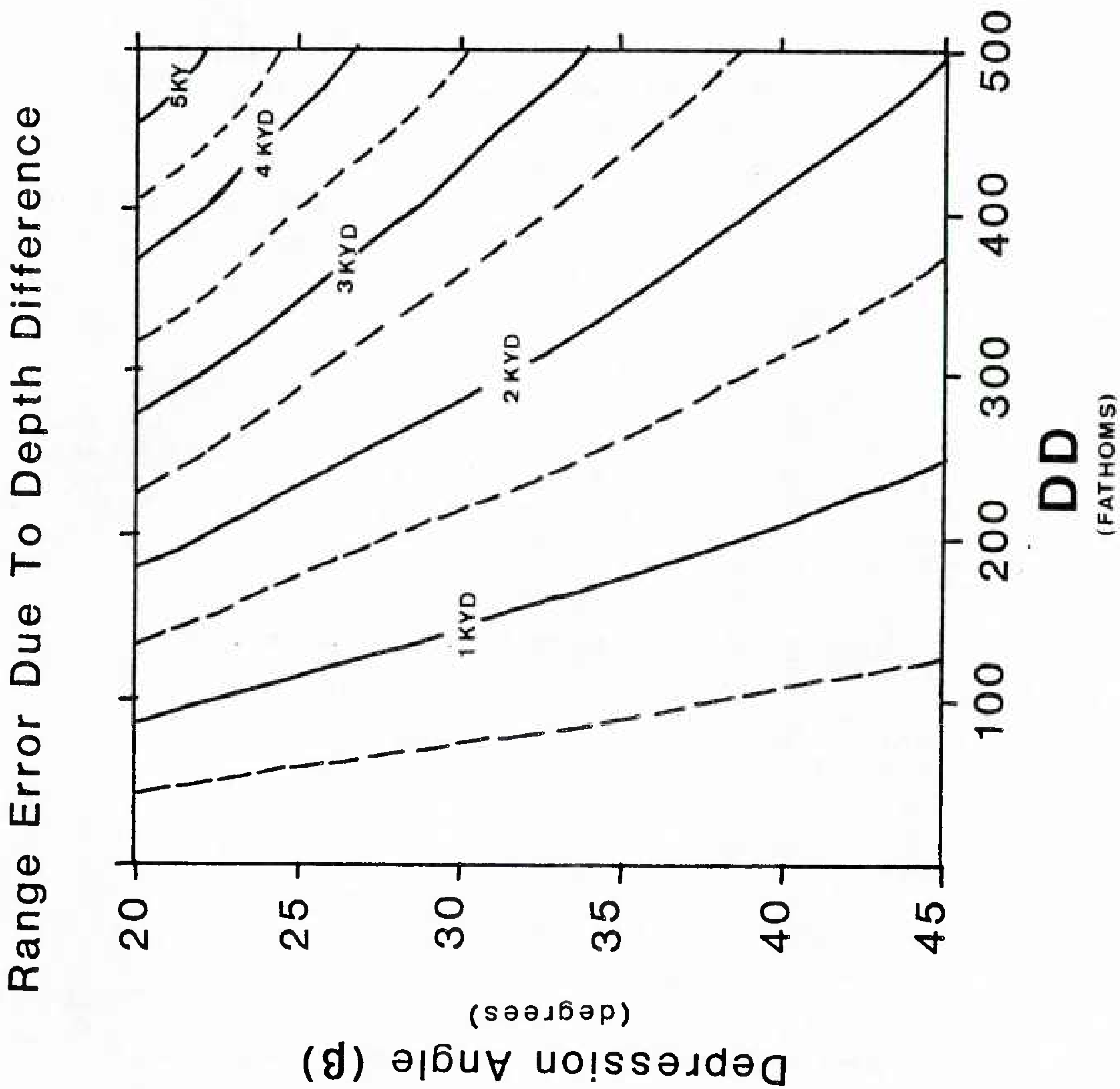


Figure 4.

Figure 5.


Range Error Due To Depth Difference
5KY
4 KYD
3 KYD
2 KYD
1 KYD
20
25
30
35
40
45
Depression Angle (β)
(degrees)
100
200
300
400
500
DD
(FATHOMS)

For this case, the bottom at the reflection point will be assumed horizontal. From figure 4 we see:

$$r = \frac{2\,(d + DD)}{\tan\beta}$$

$$= R + \frac{2DD}{\tan\beta} \qquad (2)$$

then substituting (2) into the expression for down range error:

$$E_D = \left(R + \frac{2DD}{\tan\beta}\right) - R$$

$$E_D = \frac{2DD}{\tan\beta} \qquad (3)$$

Note that the range error is independent of the absolute water depth. Figure 5 contains a plot of range error as a function of depth difference and depression angle. As can be seen from equation (3) and Figure 5, the range error increases for decreasing grazing angles and increasing depth difference.

Average Depth - Sloping Bottom Plane Model

Next, consider a bottom which has some average depth (d) but fluctuates about this depth such that the plane at the bounce point is not horizontal. This case is depicted in figure 6.

ROUGH BOTTOM WITH AN AVERAGE DEPTH

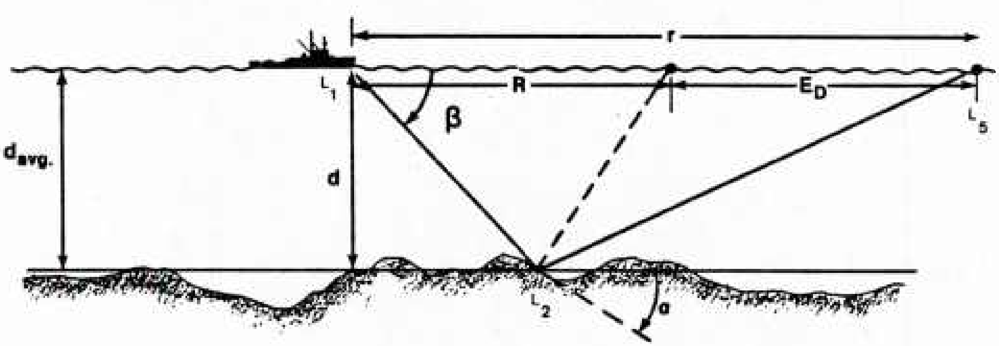


Figure 6.

To start the analysis of this case, consider the special case where the apparent bearing is in the same direction as the maximum slope direction. From figure 6 it can then easily be shown that

$$\measuredangle \overrightarrow{L_1 L_5}, \overrightarrow{L_5 L_3} = \beta - 2\alpha$$

and

$$r = R/2 + d/\tan(\beta - 2\alpha)$$

solving for the down range error:

$$E_D = d/\tan(\beta - 2\alpha) - R/2 \tag{4}$$

The down range error is seen to be a function of depth, depression angle and bottom slope.

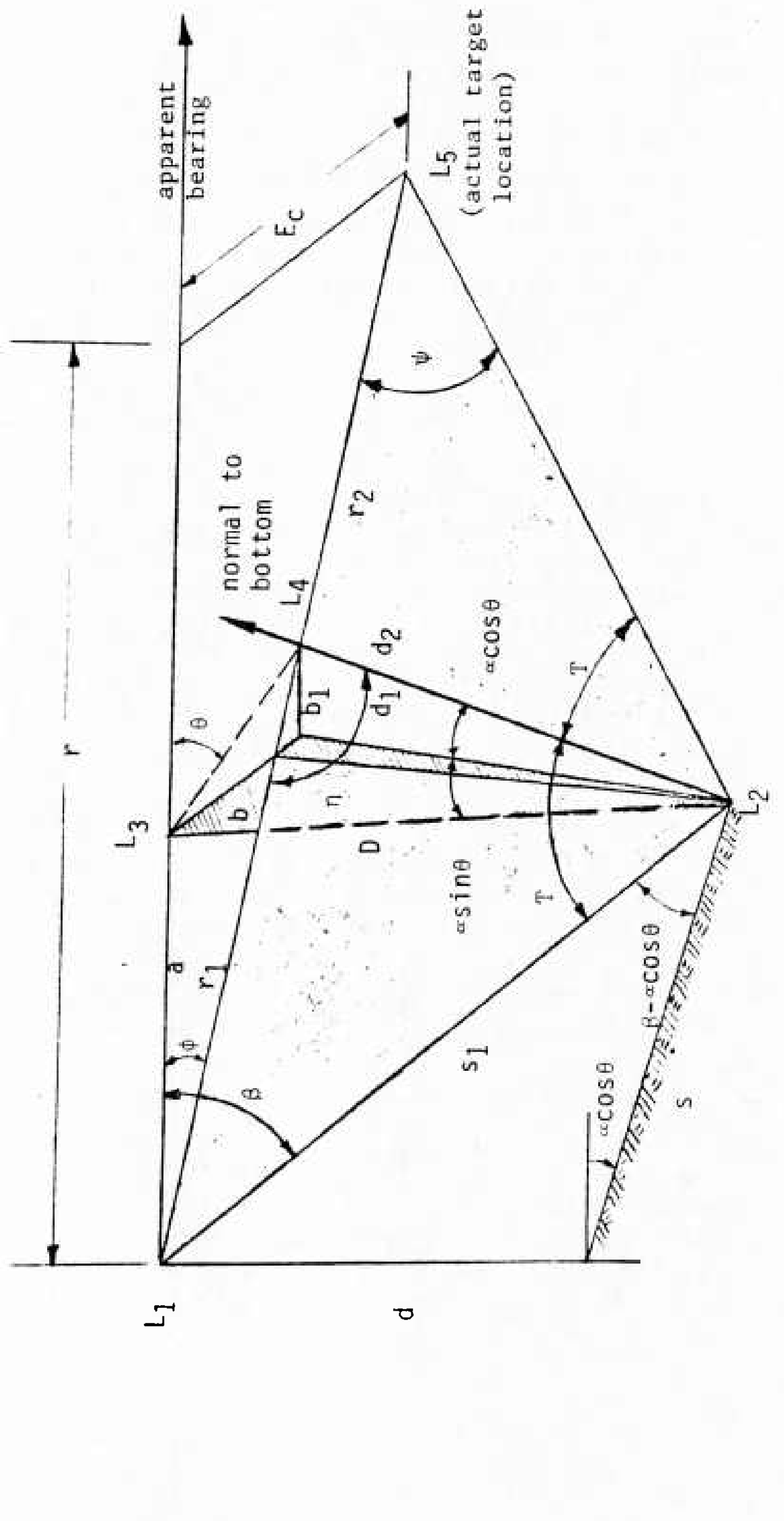
So far we have not looked at a case where a cross range error has been present. Cross range errors only occur when the vector normal to the plane at the bounce point is not contained within the vertical plane determined by the receiver and the bottom bounce point. The angle of incidence is equal to the angle of reflection in the plane containing the receiver, the normal vector at the reflection point and the target. This is called "the plane of reflections" by Officer (reference 1).

When cross slope angles (the angle between the apparent bearing and the maximum slope direction) other than zero are included in the analysis, the mathematical expressions become quite complicated. Simple expressions for the error calculations can be found by parameterizing and suppressing the variables θ, β and α (see Appendix III). Appendix I contains results for some depression angles, depths, bottom slopes and cross slope angles of interest. A discussion of the results will be included in the following section because of the similarities with the sloping bottom model.

Sloping Bottom Model

Consider an area of the ocean with a bottom which is tilted at some angle from the horizontal. If the bottom geometry is not accounted for, range errors are caused both by the depth difference and by the non-horizontal bottom plane. Figure 7 shows details of the rather complex geometry of the sloping bottom model.

The expressions for the down range and cross range errors are developed in Appendix II. Tables defining the signs of the errors for possible situations are also given in Appendix II. Numerical results for some cases of interest are given in Appendix IV. Table 1 summarizes, qualitatively, some results for both the average depth and the sloping bottom model.



Sloping Bottom Geometry

Figure 7.

Table 1
SUMMARY OF RESULTS FOR AVERAGE
DEPTH AND SLOPING BOTTOM MODEL

Variable	Comments
Depression Angle (β) (+ down)	For all other variables held constant, total range error decreases with increasing grazing angle. Results at small depression angles are subject to errors caused by neglecting refraction.
Depth (d) (+ down)	Range errors due to a nonhorizontal bounce point plane increase with increasing depth. Comparison of results for the average depth model and the sloping bottom model show that if the depth difference caused by the sloping bottom is taken into account then the sloping bottom model error is equal to the error in the average depth model plus the depth difference error.
Bottom Slope (α) (+ down)	Steeper slopes give larger range errors. The magnitude of errors due to bottom slope are not symmetric, i.e., the magnitude of a range error from a negative slope angle is smaller than that for the same positive slope angle.
Cross Slope Angle (θ) (+ clockwise)	Cross range errors occur only for nonzero θ. For increasing cross slope angle the cross range or bearing error increases, but the total range error decreases. For a given depth and nonzero bottom slope, the maximum range error is at $\theta = 0°$.

Conclusions

Using some simplifying assumptions, it has been shown that accurate bottom topography is necessary for range estimation when using bottom bounce paths. For areas with horizontal bottoms the range error introduced by a depth estimation error is independent of the absolute water depth and depends only upon the depth error and grazing angle. Sloping bottoms can introduce large range errors. These can be both down range and cross range depending upon the cross slope angle. When a slope at the bottom bounce point is present, the range error is a function of the water depth and increases with increasing water depth. The worst case scenario for range error is deep water, a small depression angle, a steeply downward sloping bottom and no cross slope angle.

References

1. Officer, C. B. (1958), Introduction to the Theory of Sound Transmission, McGraw Hill, New York.

2. Speigel, M. R. (1968), Schaum's Outline Series Mathematical Handbook, McGraw Hill, New York.

Appendices

Appendix I

Average Depth Model

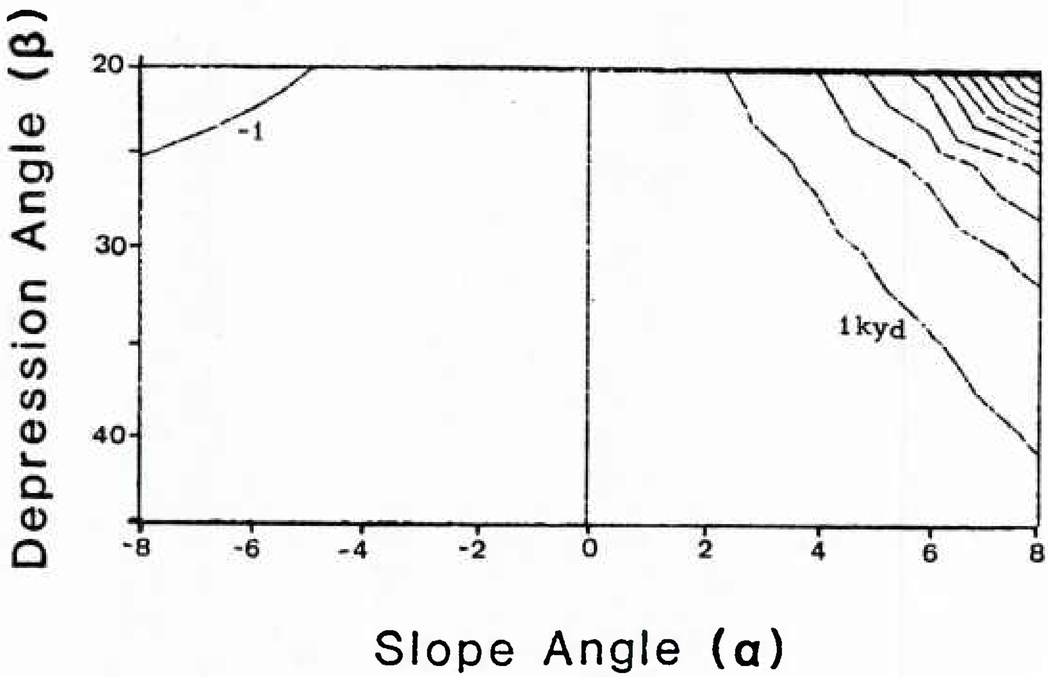
Range Errors

Average Depth Model
Appendix I

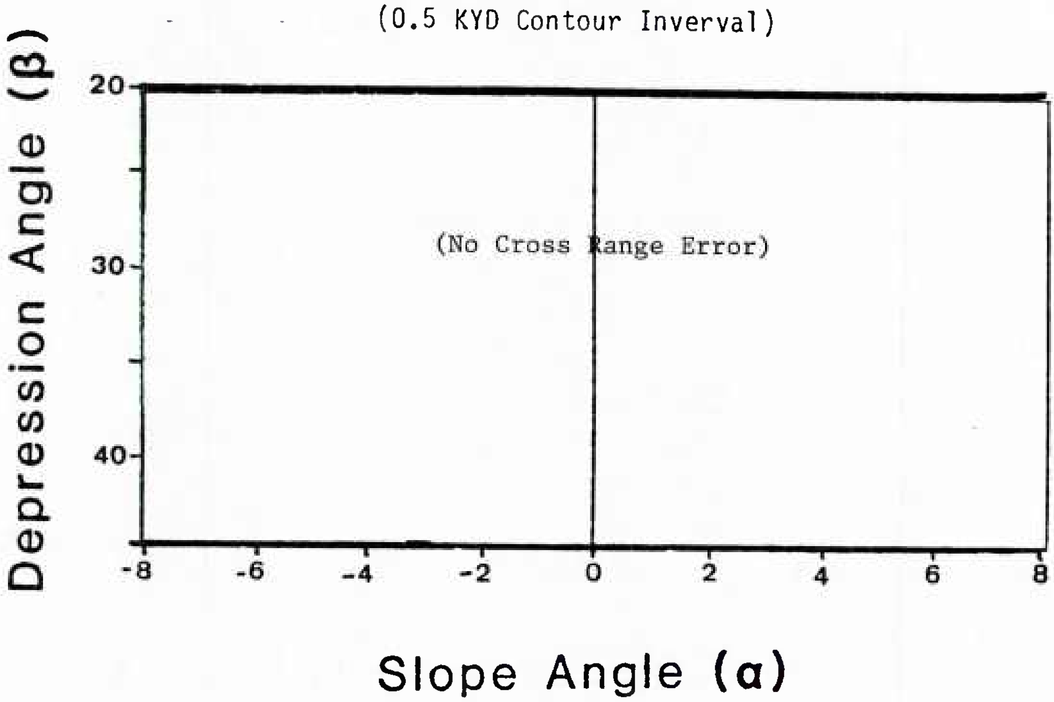
Depth 500 FM

Cross-slope (θ) 0°

DOWN RANGE ERROR
(1 KYD Contour Interval)



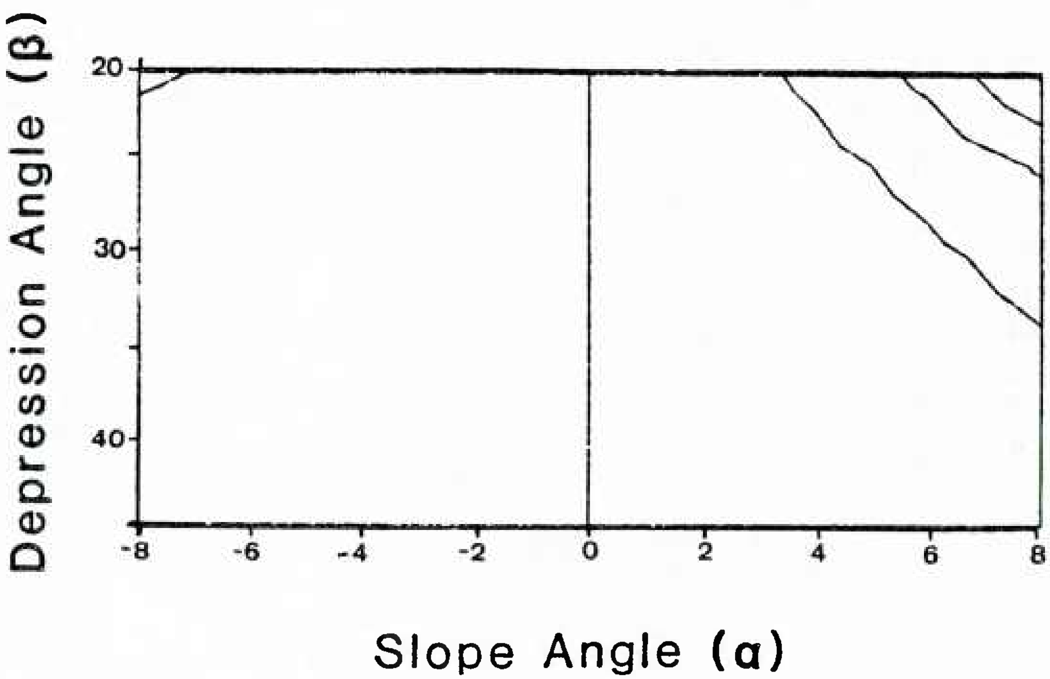
CROSS RANGE ERROR
(0.5 KYD Contour Inverval)



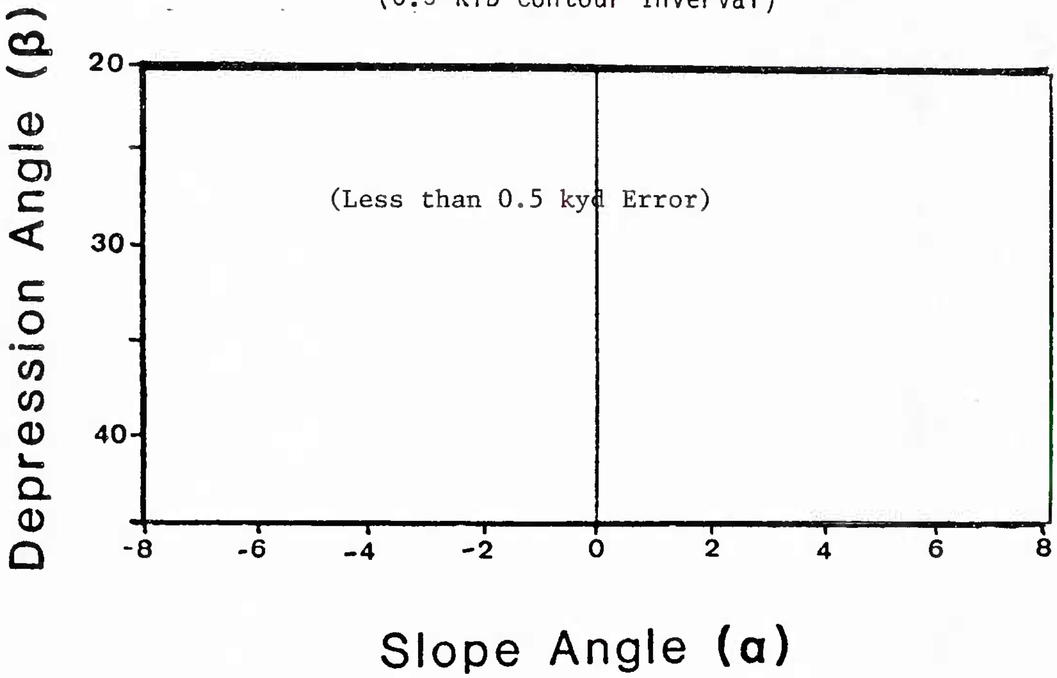
Depth 500 FM

Cross-slope (θ) 45°

DOWN RANGE ERROR
(1 KYD Contour Interval)



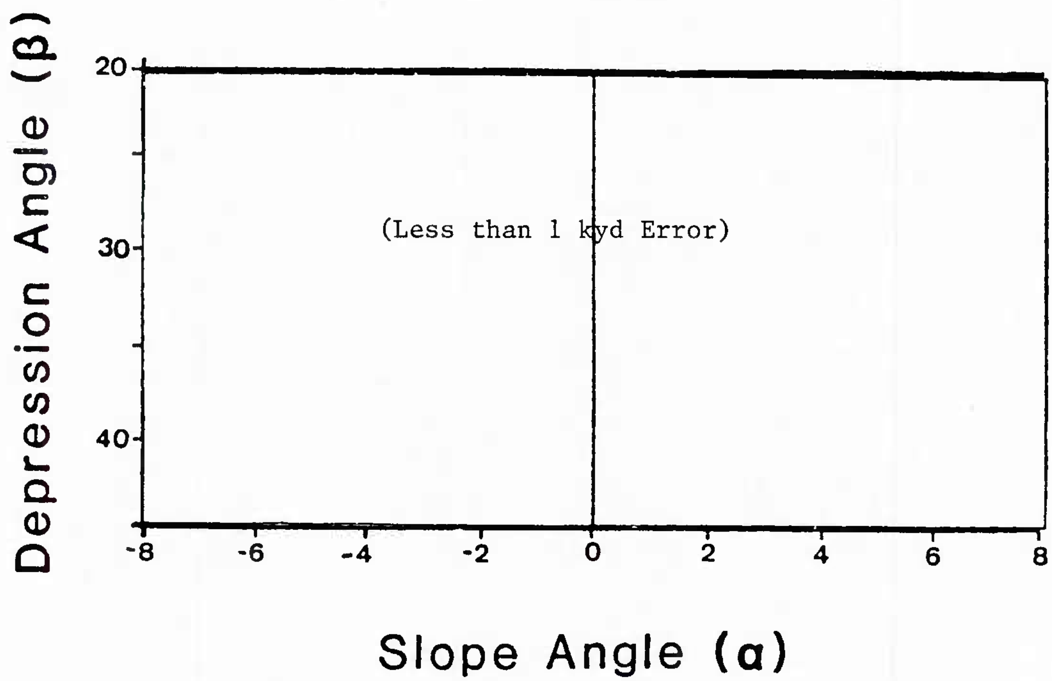
CROSS RANGE ERROR
(0.5 KYD Contour Inverval)



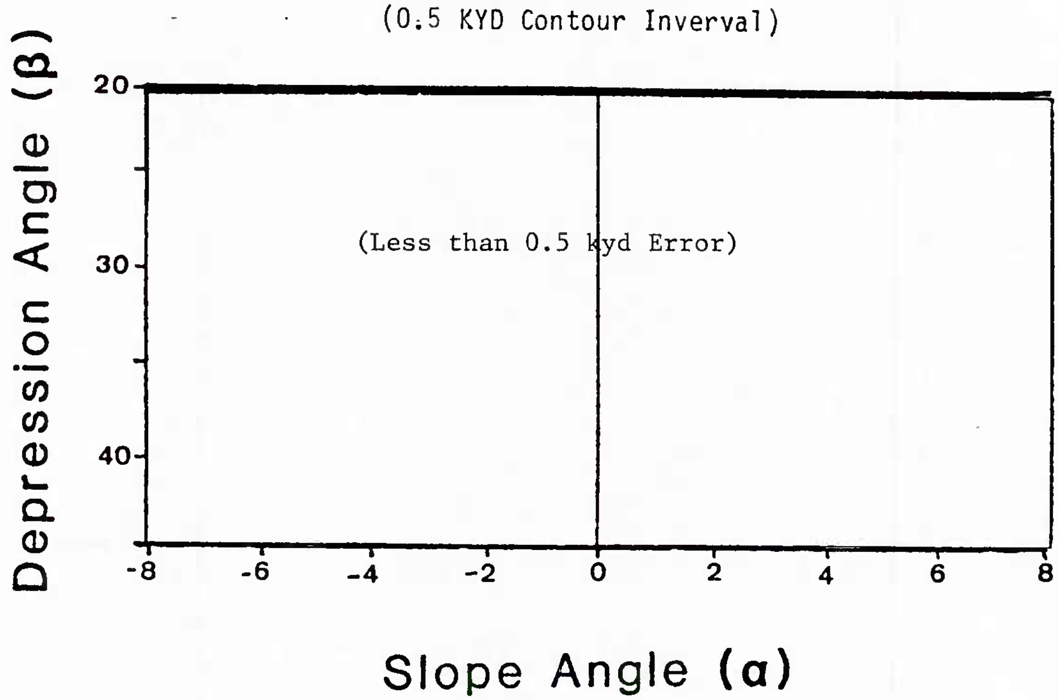
Depth 500 FM

Cross-slope (θ) 90°

DOWN RANGE ERROR
(1 KYD Contour Interval)



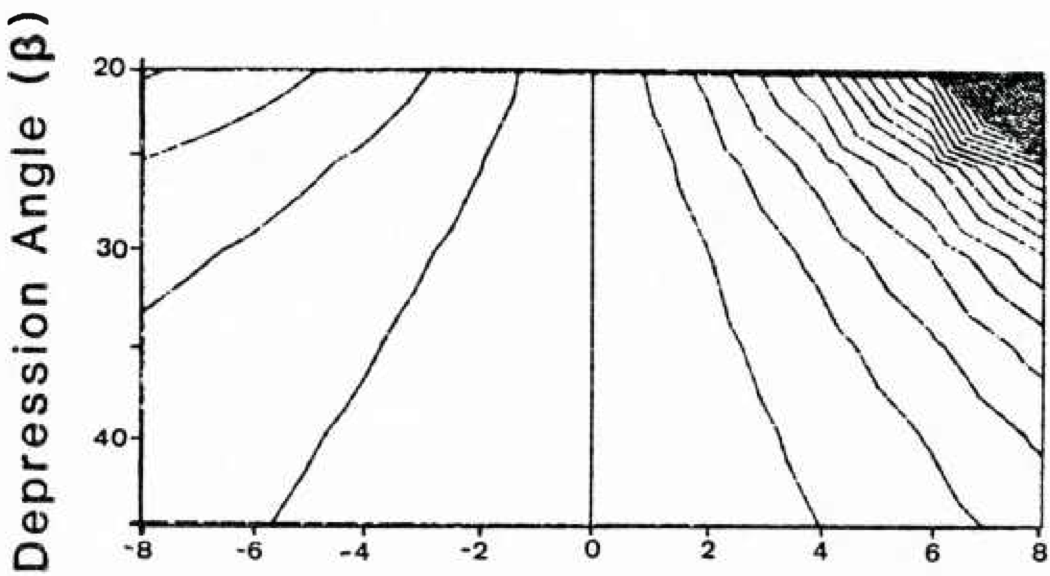
CROSS RANGE ERROR
(0.5 KYD Contour Inverval)



Depth 1500 FM

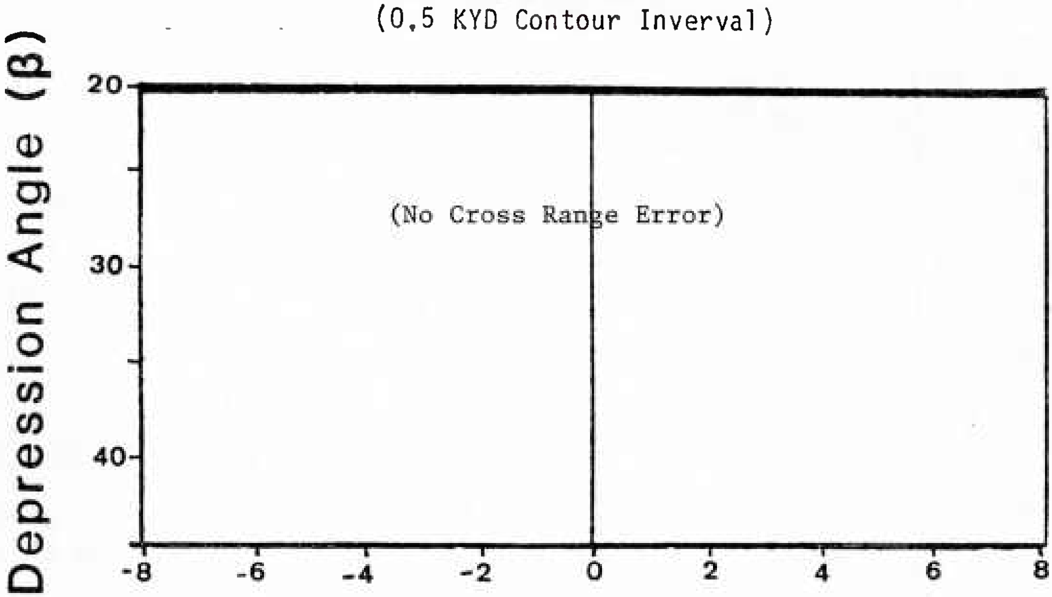
Cross-slope (θ) 0°

DOWN RANGE ERROR
(1 KYD Contour Interval)



Slope Angle (α)

CROSS RANGE ERROR
(0.5 KYD Contour Inverval)

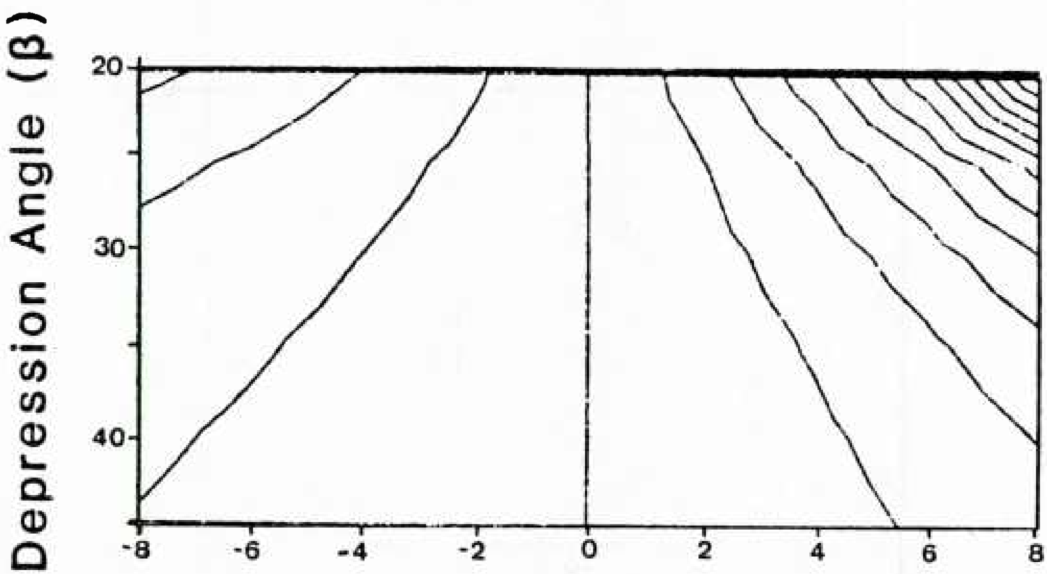


Slope Angle (α)

Depth 1500 FM

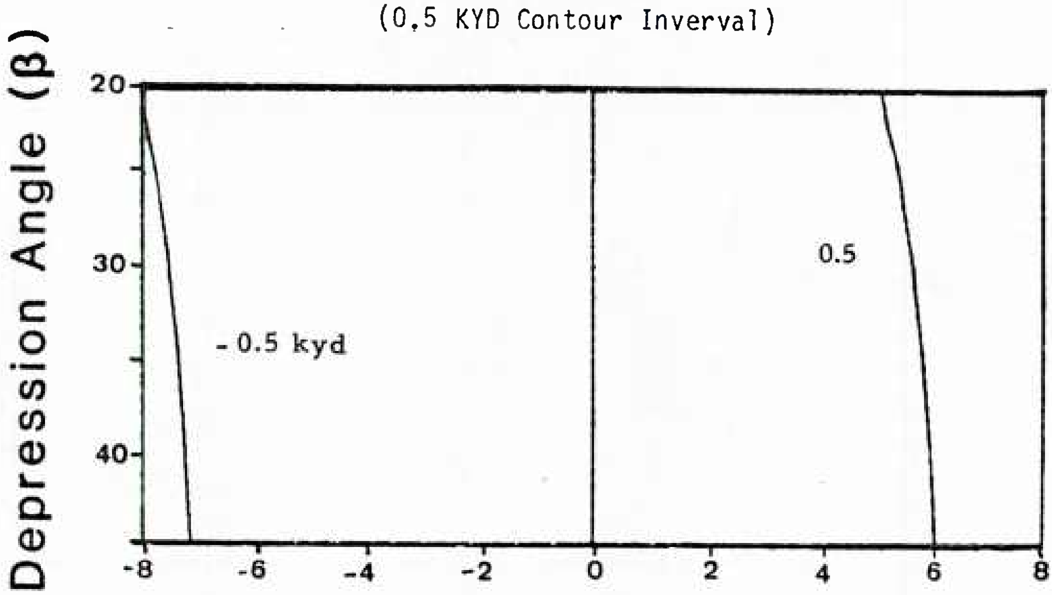
Cross-slope (θ) 45°

DOWN RANGE ERROR
(1 KYD Contour Interval)



Slope Angle (α)

CROSS RANGE ERROR
(0.5 KYD Contour Inverval)

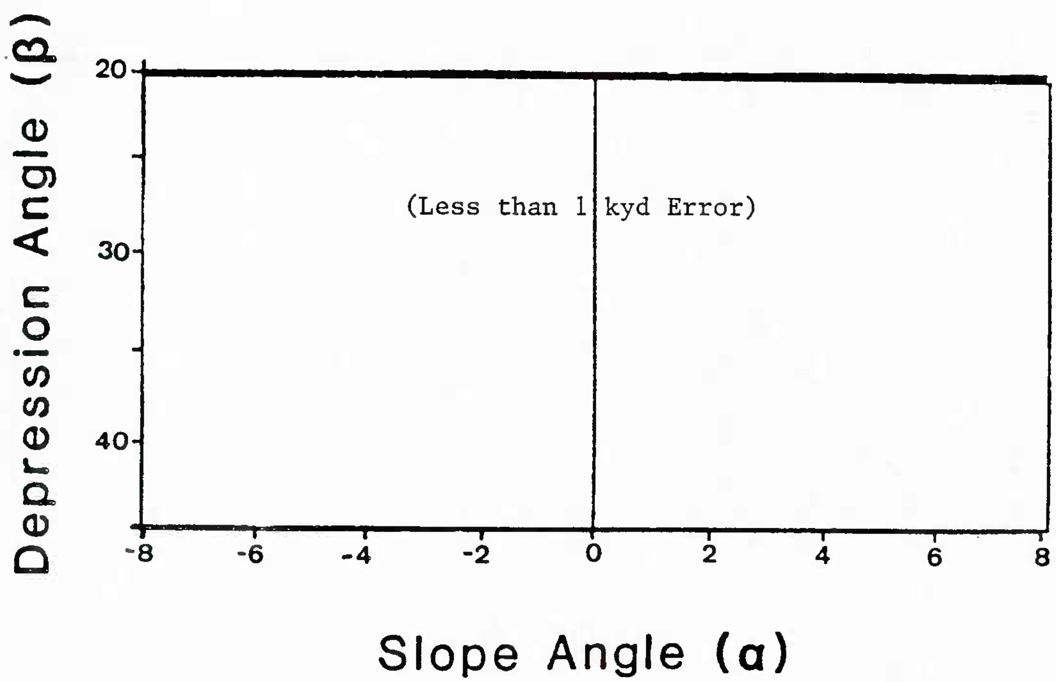


Slope Angle (α)

Depth 1500 FM

Cross-slope (θ) 90°

DOWN RANGE ERROR
(1 KYD Contour Interval)



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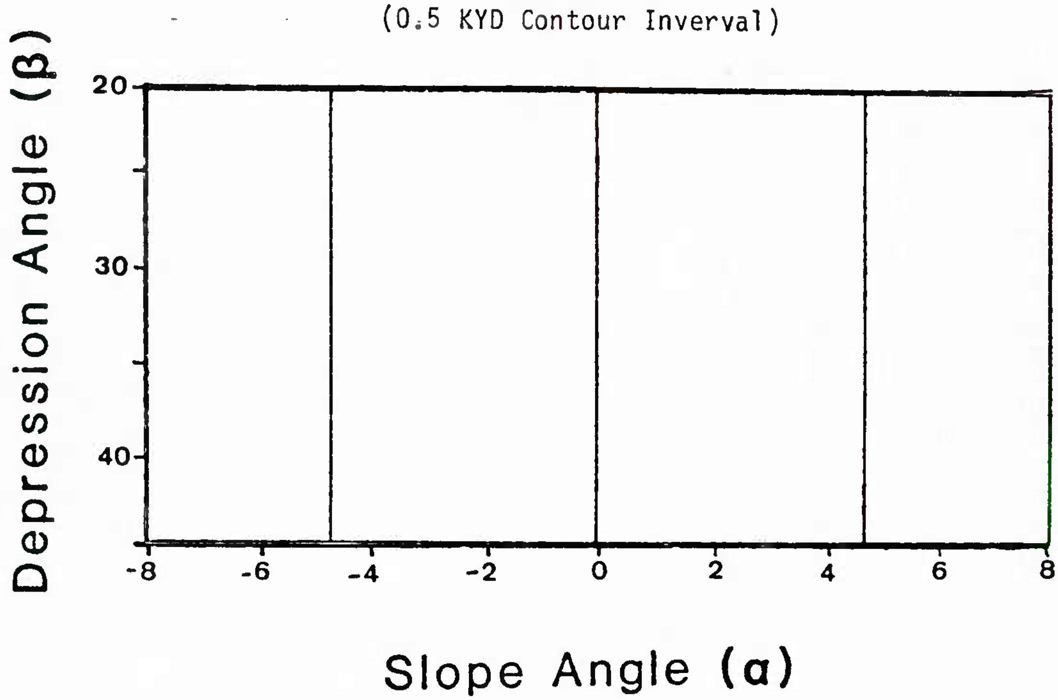
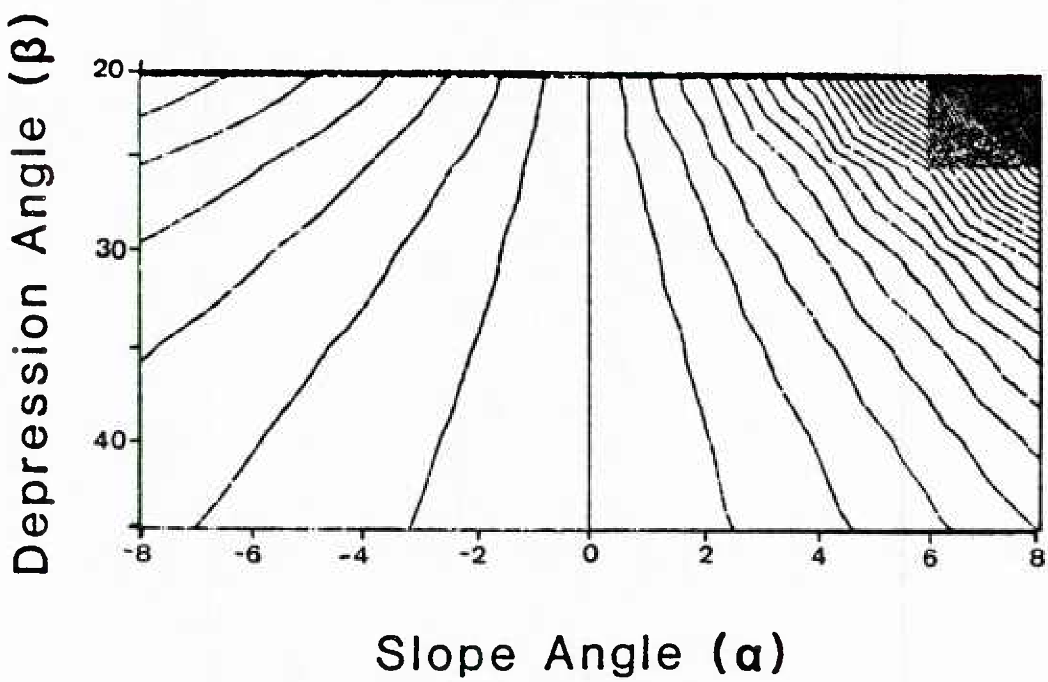
(0.5 KYD Contour Inverval)



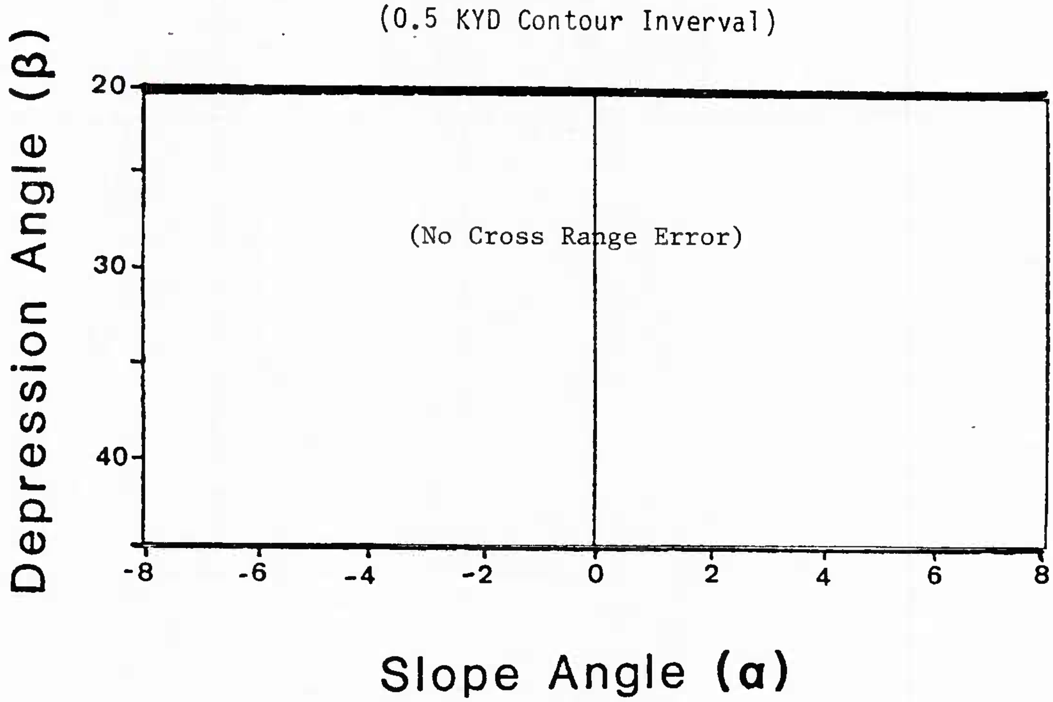
Depth 2500 FM

Cross-slope (θ) 0°

DOWN RANGE ERROR
(1 KYD Contour Interval)



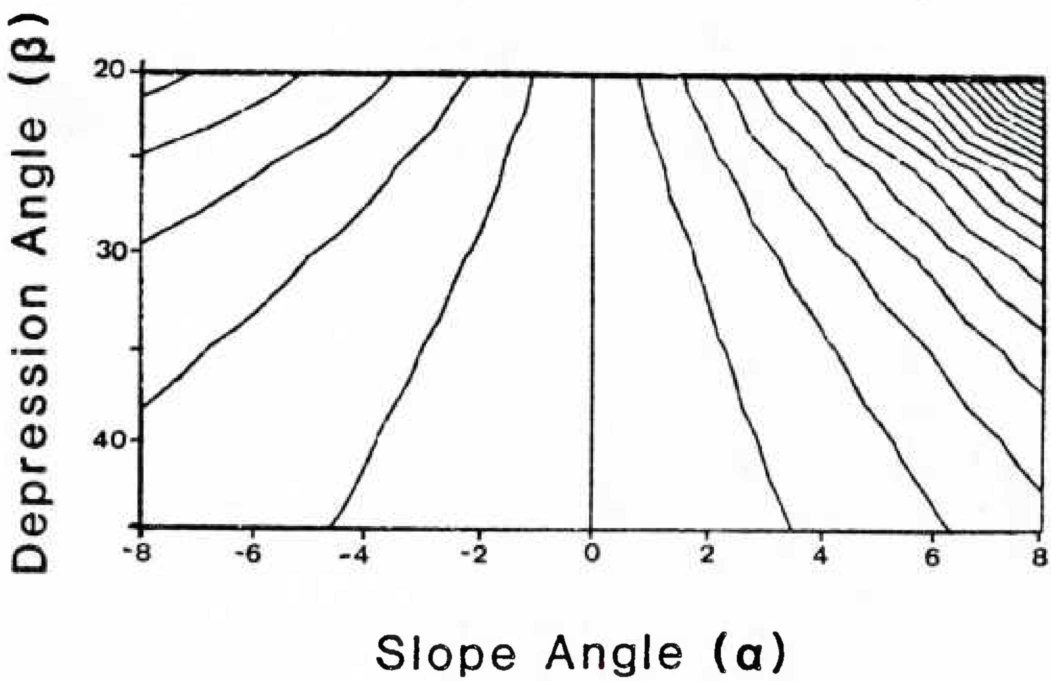
CROSS RANGE ERROR
(0.5 KYD Contour Inverval)



Depth 2500 FM

Cross-slope (θ) 45°

DOWN RANGE ERROR
(1 KYD Contour Interval)



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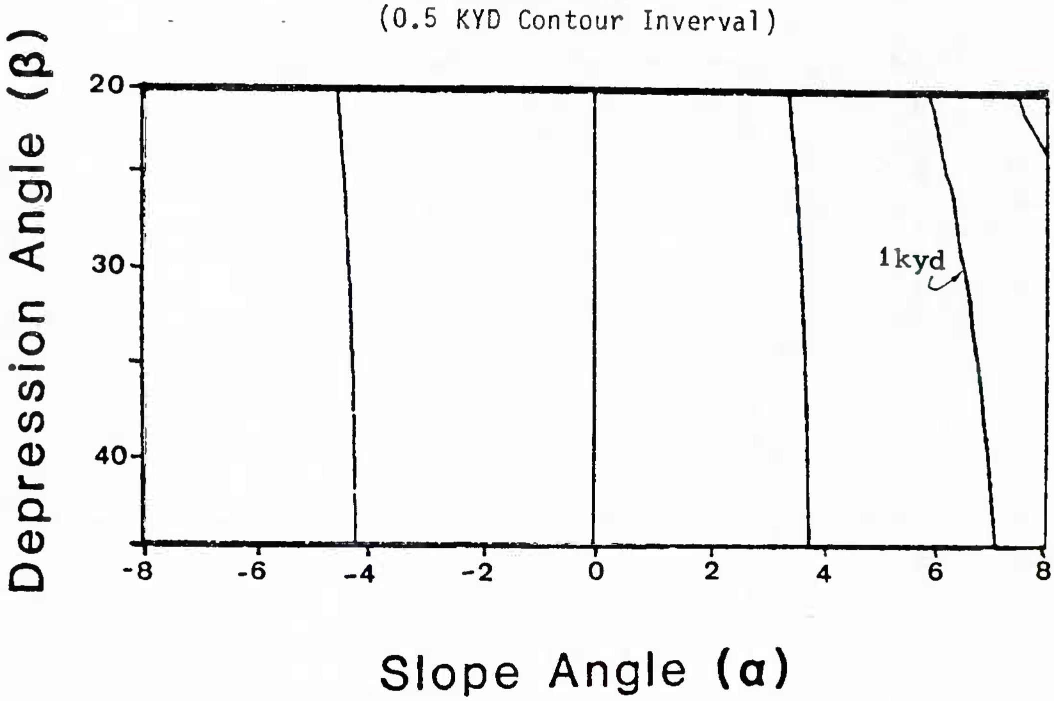
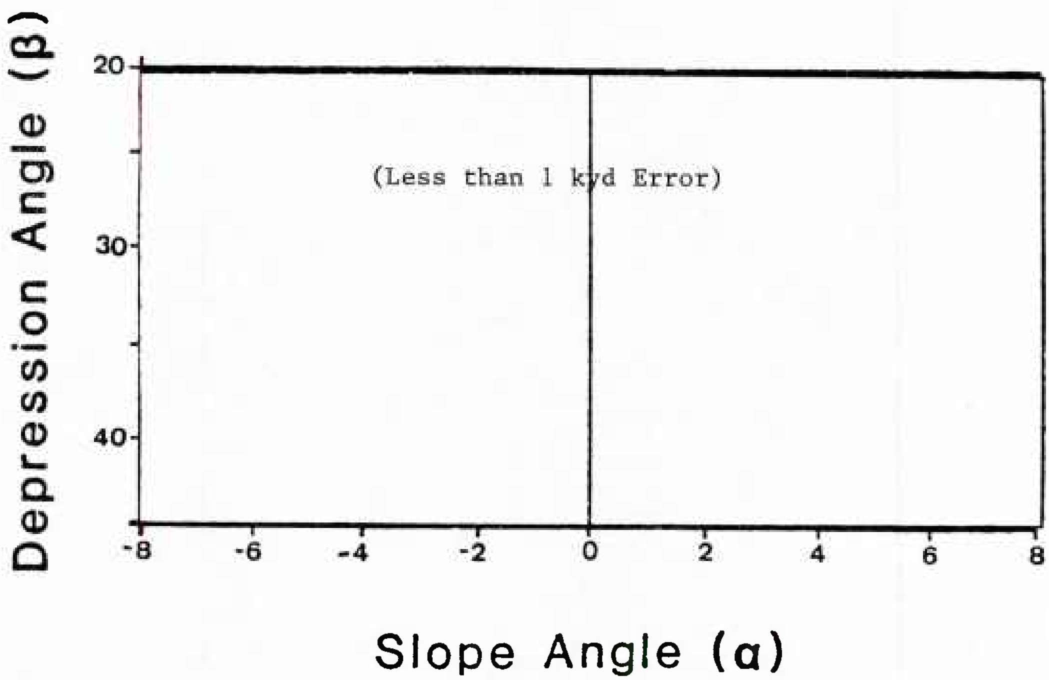
(0.5 KYD Contour Inverval)



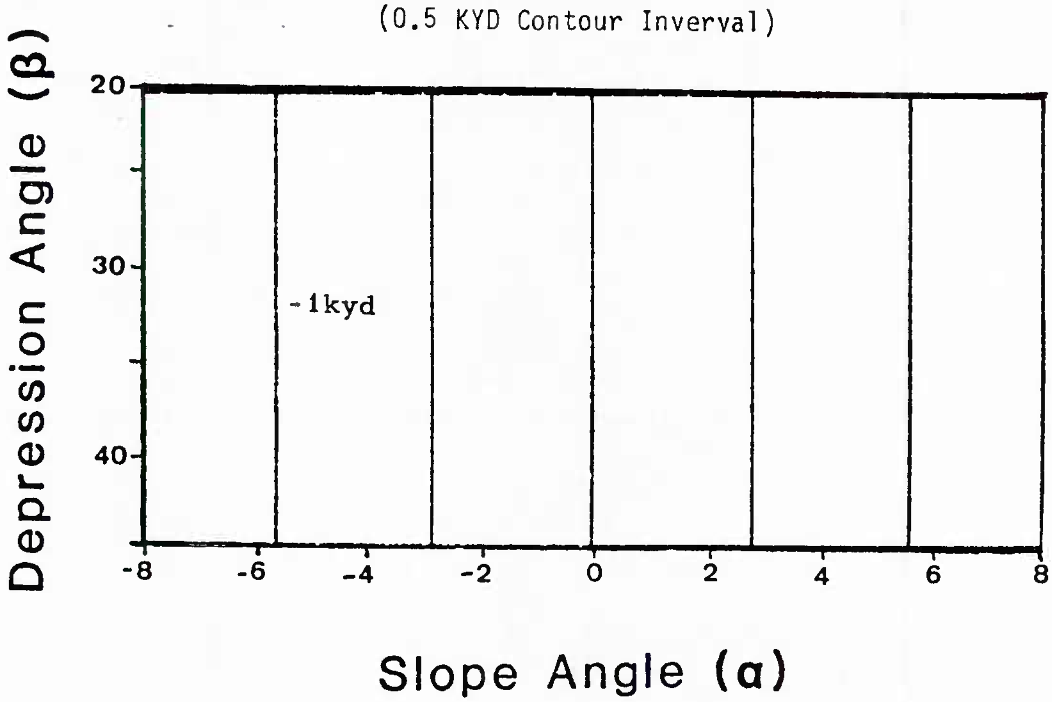
Depth 2500 FM

Cross-slope (θ) 90°

DOWN RANGE ERROR
(1 KYD Contour Interval)



CROSS RANGE ERROR
(0.5 KYD Contour Inverval)



APPENDIX II

Derivation of sloping bottom model

A. Small Slope Approximation

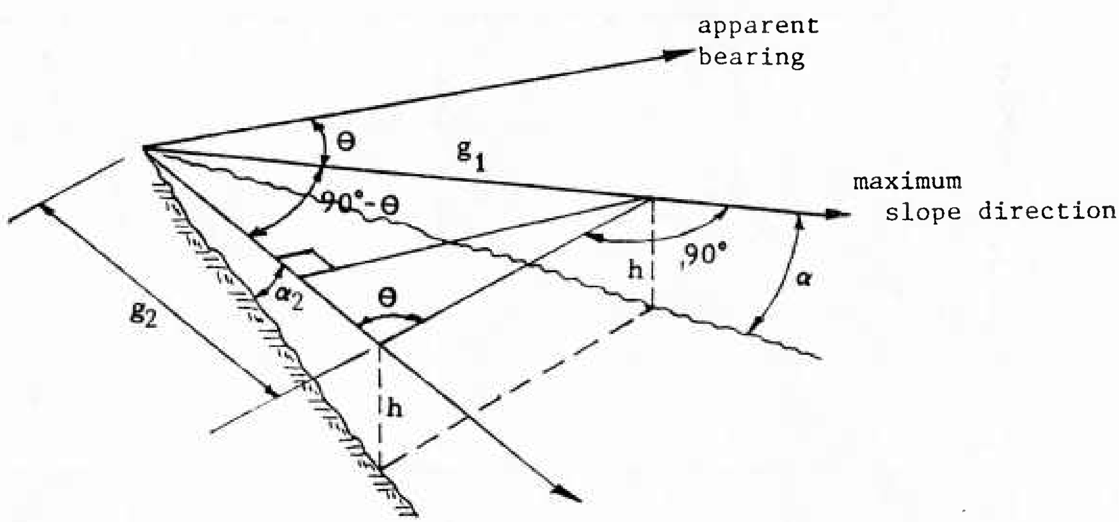


Figure II - 1

The bottom slope is defined as:

$$S_1 = (h/g_1)$$

and

$$\alpha = \tan^{-1}(S_1).$$

But for small x, $\tan^{-1}x \approx x$

Therefore,

$$\alpha \approx (h/g_1)$$

then from the above figure, the slope component at 90° to the apparent bearing is:

$$S_2 = h/g_2$$

$$\text{but } g_2 = g_1/\sin\theta$$

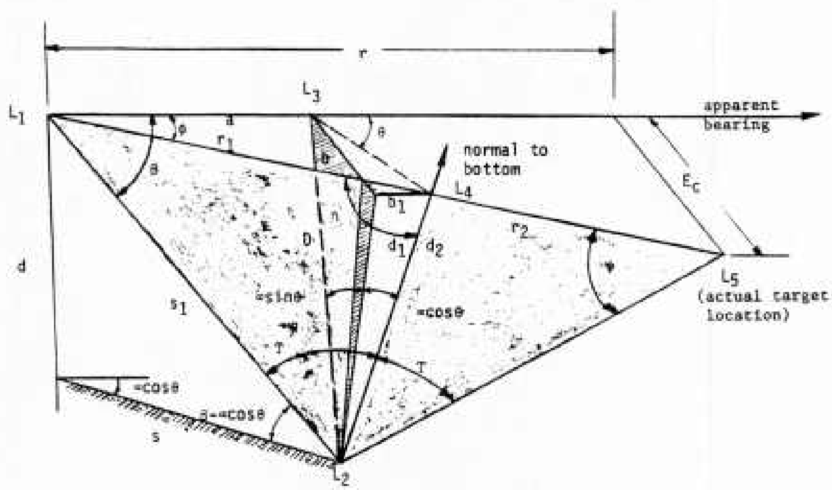
$$\alpha_2 = \tan^{-1}\left(\frac{h}{g_1}\sin\theta\right) \approx \alpha \sin\theta$$

A similar development gives the component in the apparent bearing direction as $\alpha \cos \theta$.

B. Derivation of Down Range and Cross Range Errors

This derivation uses the small slope approximation, shown above. The final form for the expessions is not explicitly expressed in terms of the variables d, β and θ, but is a parameterization. These parameters are derived in a step by step manner then combined to give the final expressions.

To start, consider figure 5, reproduced here for convenience.



Sloping Bottom Geometry

Fig II-2

The slant range to the bounce point (S_1) is given by

$$|\overrightarrow{L_1L_2}| = S_1 = d \frac{\sin (90 + \alpha\cos\theta)}{\sin (\beta - \alpha\cos\theta)}$$

$$= d \frac{\cos(\alpha\cos\theta)}{\sin(\beta - \alpha\cos\theta)}$$

the down range distance to the bounce point is:

$$|\overrightarrow{L_1L_3}| = a = S_1\cos\beta$$

the depth at the bounce point is:

$$|\overrightarrow{L_3L_2}| = D = S_1\sin\beta.$$

Now two rotations must be made for the two bottom slope components.

1) $b = D \tan(\alpha \sin\theta)$ (cross range deflection)

$d_1 = \sqrt{b^2 + D^2}$ (slant depth)

2) $b_1 = D \tan(\alpha \cos\theta)$ (down range deflection)

$d_2 = \sqrt{b_1^{\,2} + d_1^{\,2}}$ (slant depth-normal to bottom)

Calculating the distance $|\overrightarrow{L_1L_4}|$ we have

$$|\overrightarrow{L_1L_4}| = r_1 = \sqrt{(a + b_1)^2 + b^2} \quad .$$

We now have the information required to calculate the angles in the triangle L_1-L_2-L_4. Using equation 5.95 from reference 2 the triangle semiperimeter is given by:

$$s = \frac{1}{2}(r_1 + d_2 + s_1)$$

and

$$\xi = 2\sqrt{s(s - r_1)(s - d_2)(s - s_1)}$$

therefore the angle γ is given by:

$$\gamma = \sin^{-1}(\xi/(d_2 s_1))$$

and η is given by

$$\eta = 180° - \gamma - \sin^{-1}(\xi/(r_1 s_1)).$$

Now since the angle of incidence $(90° - \gamma)$ is equal to the angle of reflection in this plane we know that the angle

$$\measuredangle\, \overrightarrow{L_4L_2}, \overrightarrow{L_2L_5} = \gamma.$$

Since

$$\psi = \eta - \gamma$$

we may calculate the range $|\overrightarrow{L_4L_5}|$

$$|\overrightarrow{L_4L_5}| = r_2 = \frac{d_2 \sin\gamma}{\sin\psi}$$

The cross range error can now be computed.

$$E_c = (r_1 + r_2) \sin\phi$$

noting $\sin \phi = \frac{b}{r_1}$

$$E_c = b\ (1 + r_2/r_1) \quad .$$

And finally the down range error is given by:

$$E_D = (r_1 + r_2) \cos \phi - R$$

$$= (r_1 + r_2) \frac{(a + b_1)}{r_1} - R$$

$$E_D = (a + b_1)\ (1 + r_2/r_1) - R.$$

C. Sign conventions

The apparent bearing can be in one of 4 quadrants as shown in figure II-3.

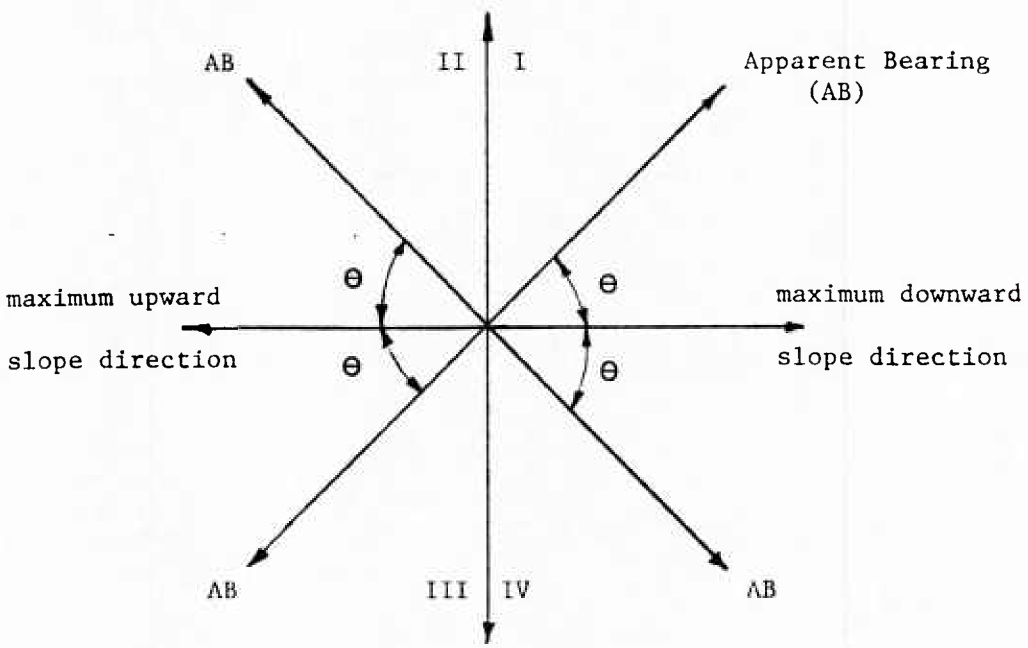


Figure II-3

Referring to the quadrants designated in figure II-3 the signs of the slope angle α and the cross slope angle θ are given in Table II-1 and the sign of the range errors is given in Table II-2.

θ \ α	+	-
+	I	III
-	IV	II

Table II-1

E_D \ E_C	+	-
+	I	IV
-	II	III

Table II-2

Appendix III

Derivation of Average Depth Case

This can be seen as a special case of the general slope model in Appendix II in which

$$a = R/2$$
$$D = d$$

then using the same variables as in Appendix II

$$s_1 = d/\sin\beta$$

$$d_1 = d/\cos(\alpha \sin\theta),$$

$$b = d \tan(\alpha \sin\theta),$$

$$b_1 = d \tan(\alpha \cos\theta),$$

$$d_2 = \sqrt{d_1^2 + b_1^2}$$

$$r_1 = \sqrt{(R/2 + b_1)^2 + b^2}.$$

The above expressions can now be used directly in the remaining expressions developed in Appendix II. It can be shown that for the special case of $\theta = 0°$, the resulting expression is equation (4) in the text.

Appendix IV

Sloping Bottom Model

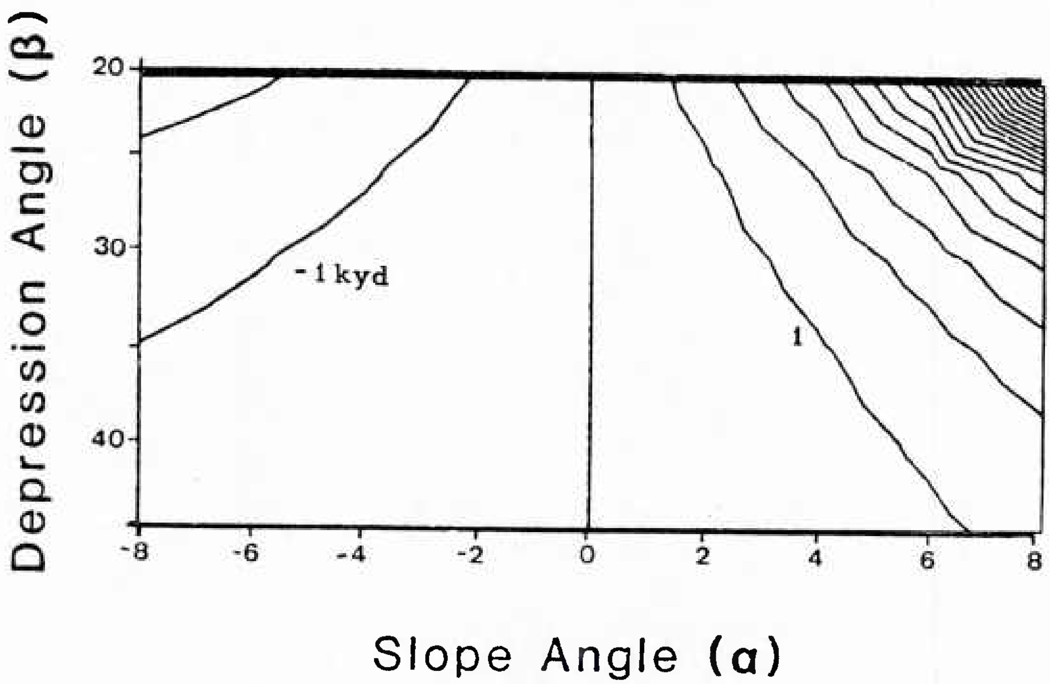
Range Errors

Sloping Bottom Model
Appendix IV

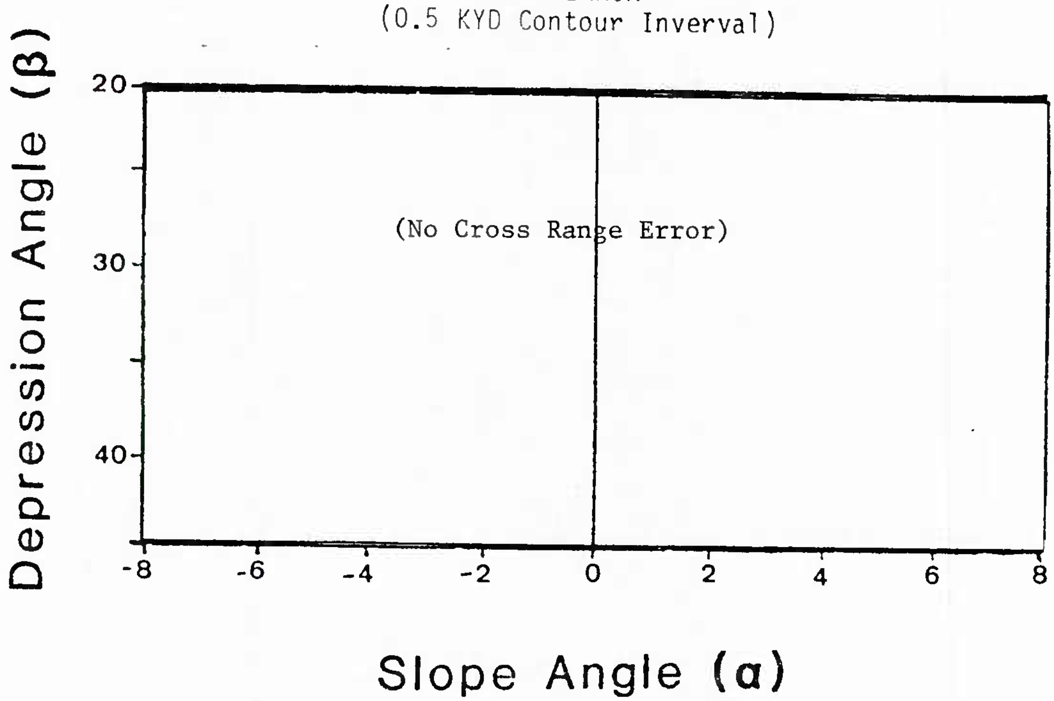
Depth 500 FM

Cross-slope (θ) 0°

DOWN RANGE ERROR
(1 KYD Contour Interval)



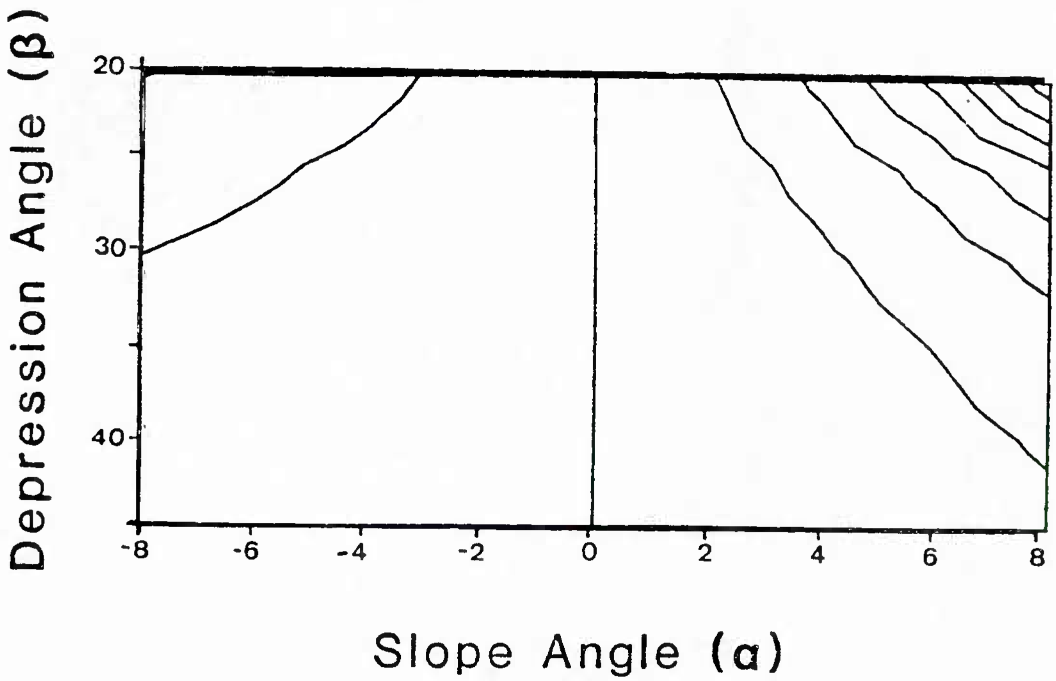
CROSS RANGE ERROR
(0.5 KYD Contour Inverval)



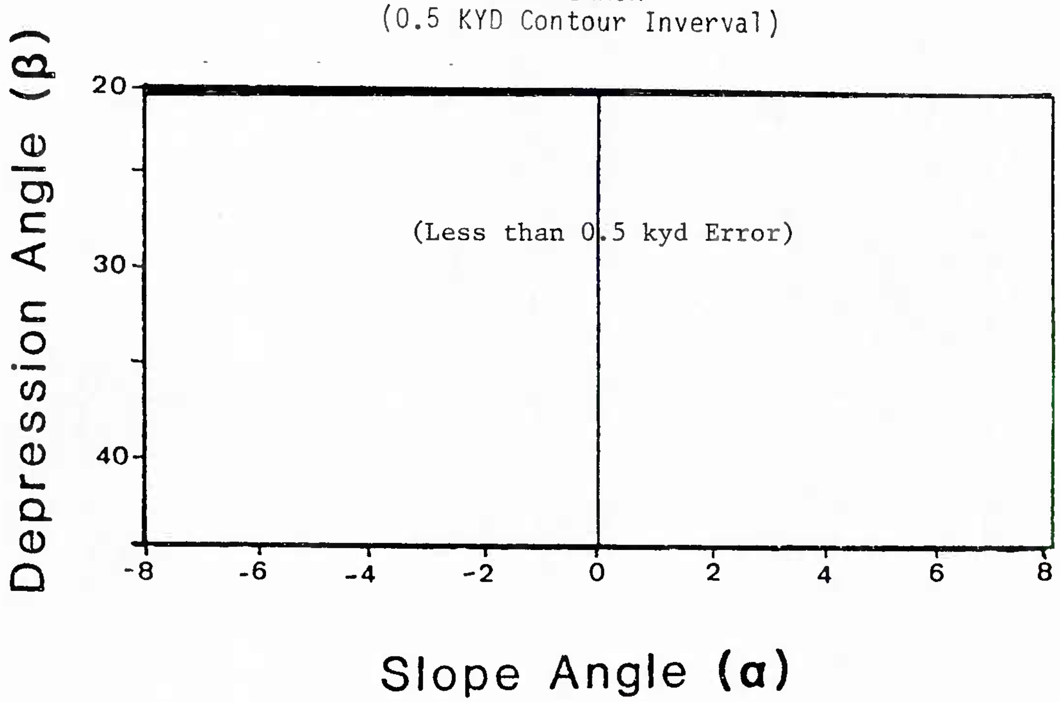
Depth 500 FM

Cross-slope (θ) 45°

DOWN RANGE ERROR
(1 KYD Contour Interval)



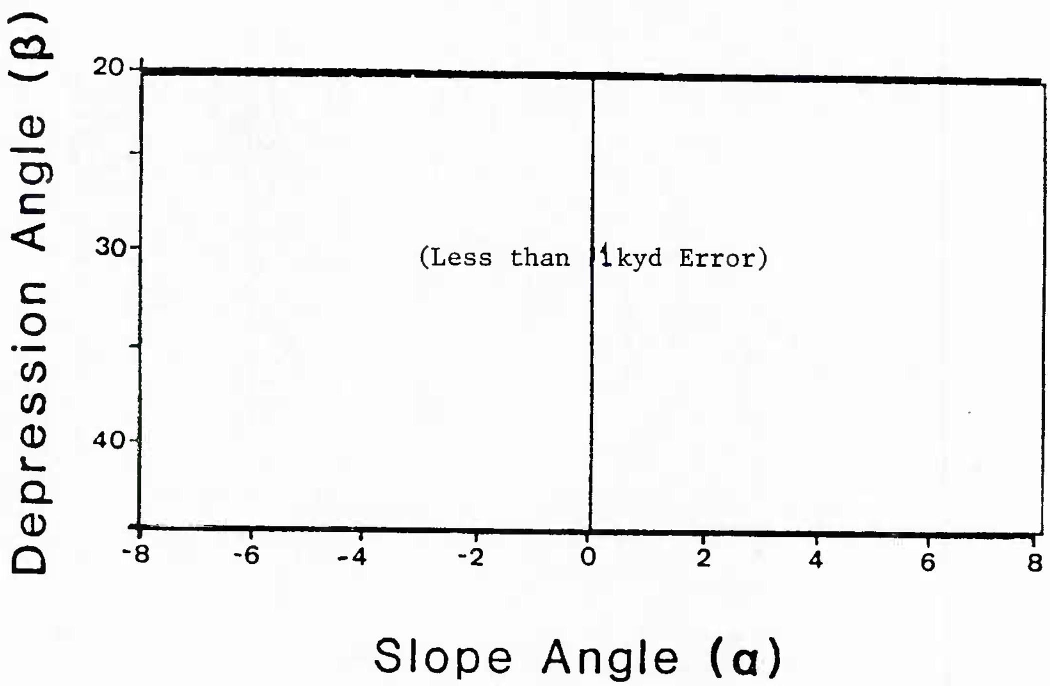
CROSS RANGE ERROR
(0.5 KYD Contour Inverval)



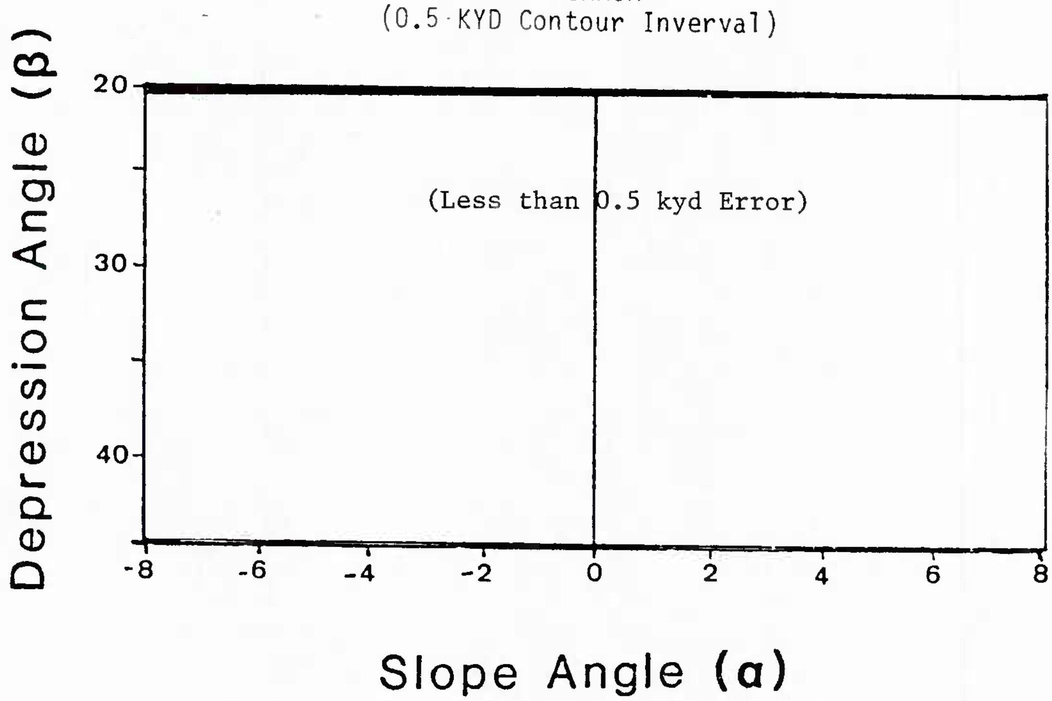
Depth 500 FM

Cross-slope (θ) 90 °

DOWN RANGE ERROR
(1 KYD Contour Interval)



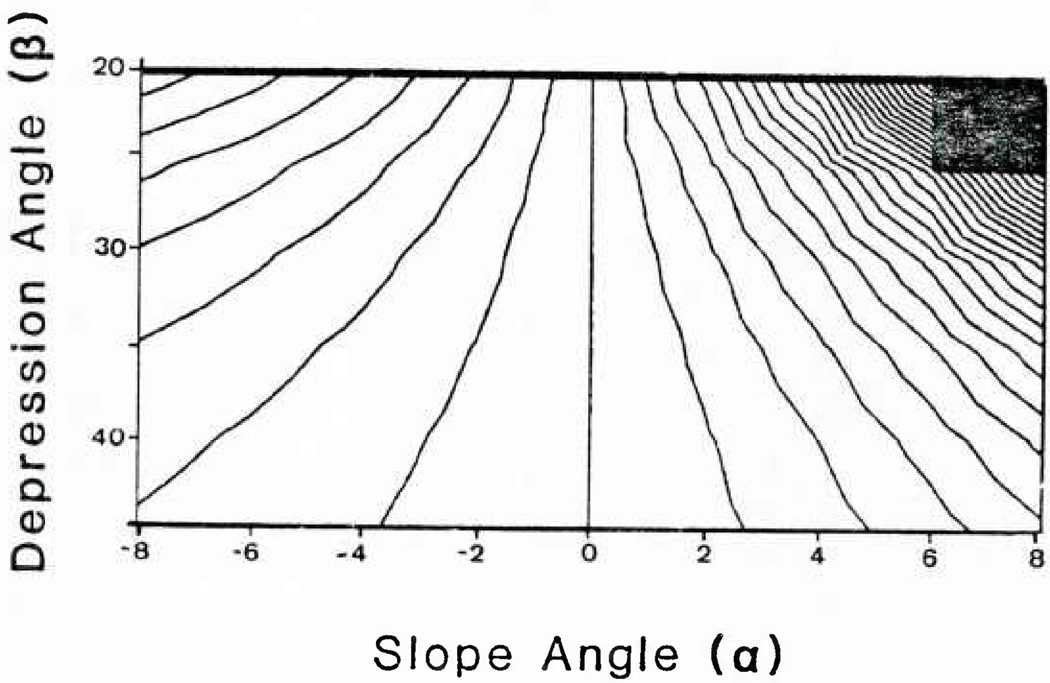
CROSS RANGE ERROR
(0.5 KYD Contour Inverval)



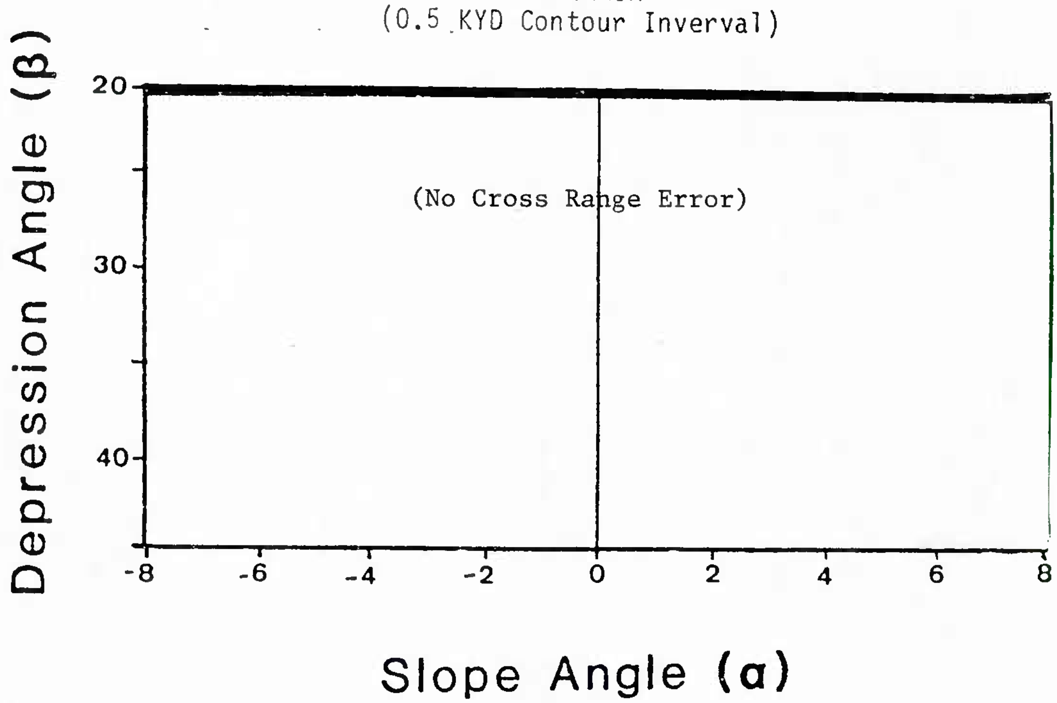
Depth 1500 FM

Cross-slope (θ) 0°

DOWN RANGE ERROR
(1 KYD Contour Interval)



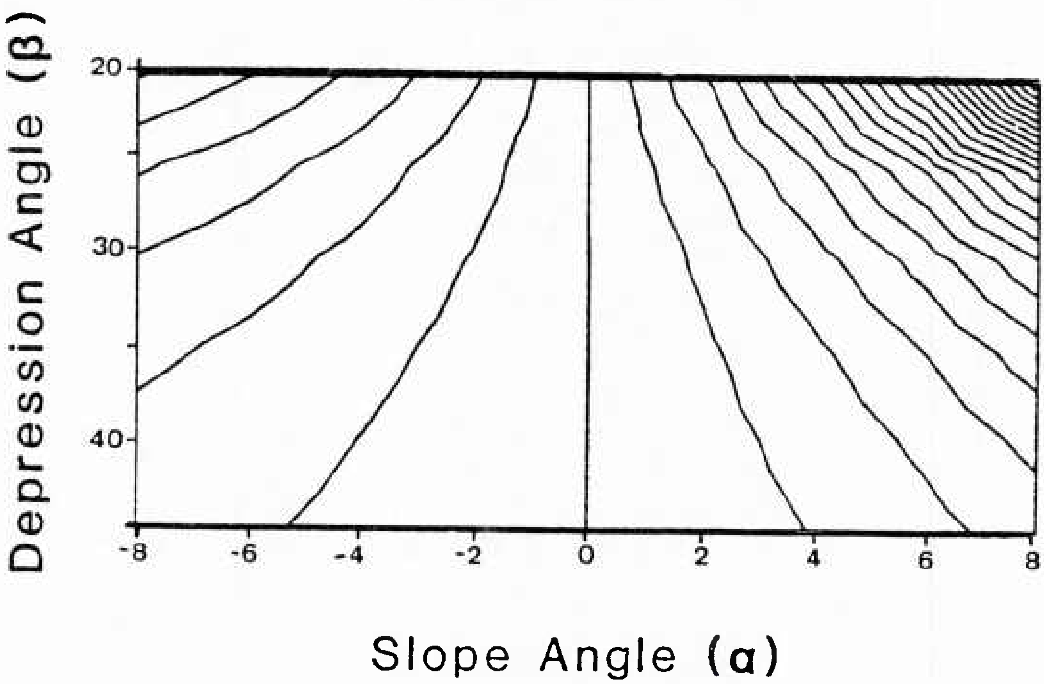
CROSS RANGE ERROR
(0.5 KYD Contour Inverval)



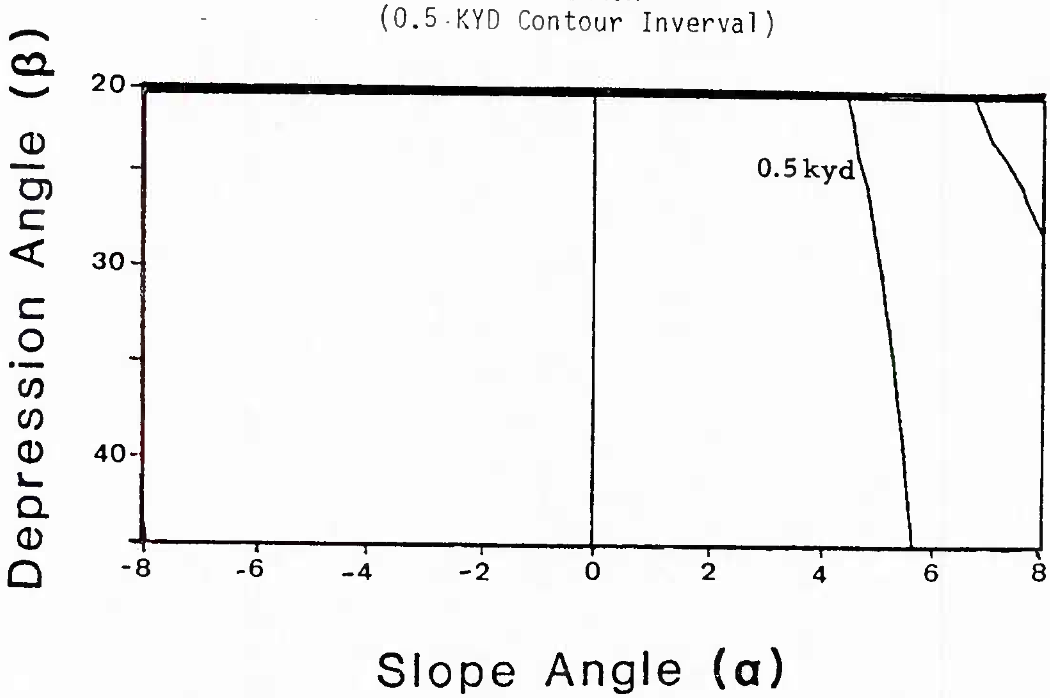
Depth 1500FM

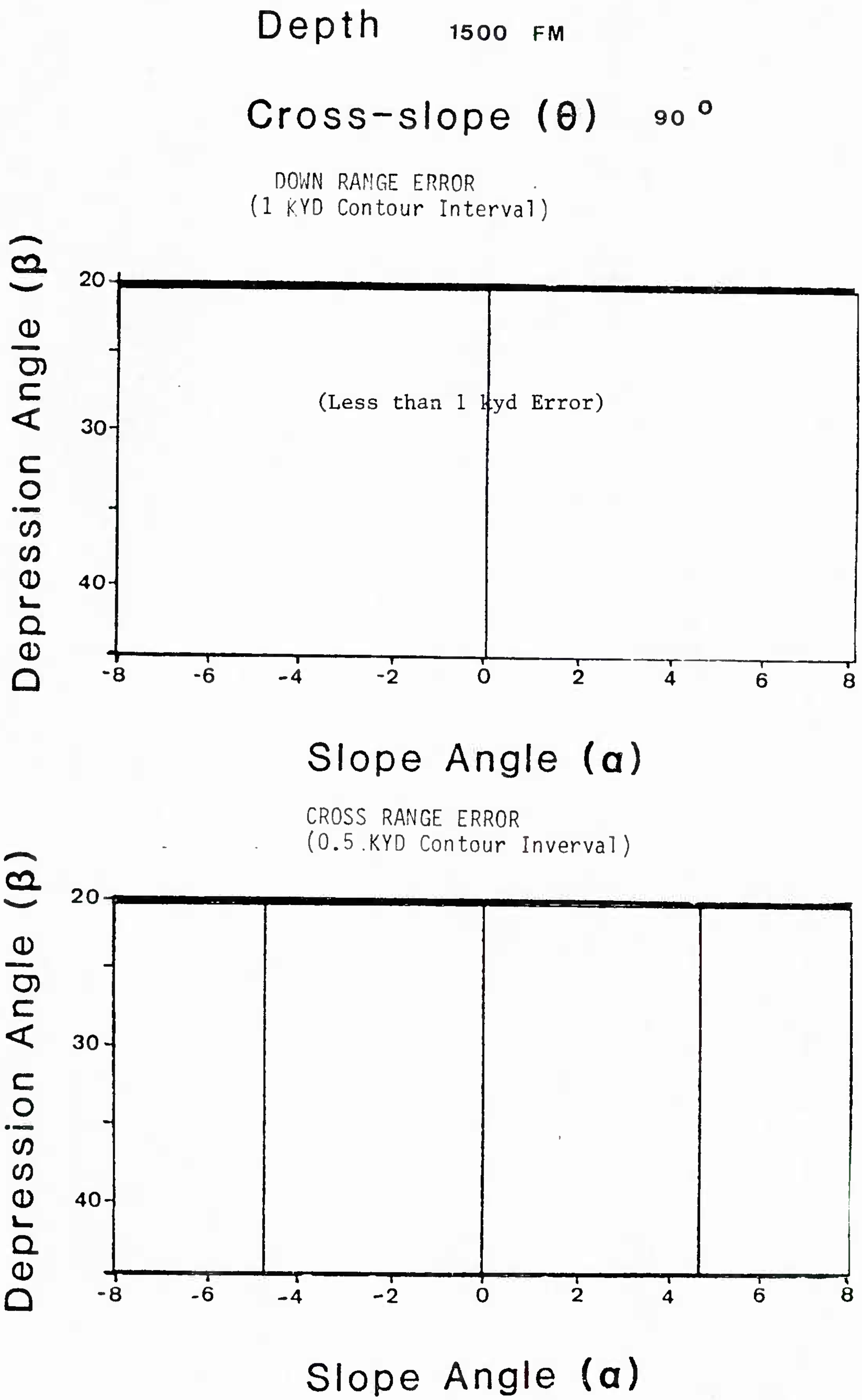
Cross-slope (θ) 45°

DOWN RANGE ERROR
(1 KYD Contour Interval)



CROSS RANGE ERROR
(0.5 KYD Contour Inverval)

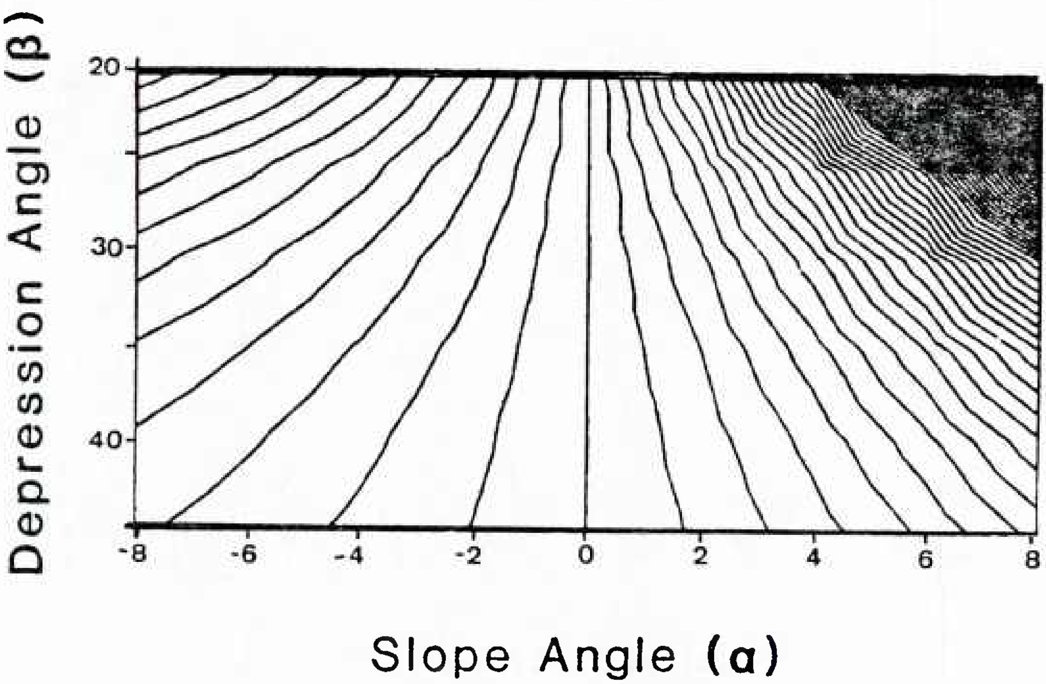



Depth 1500 FM
Cross-slope (θ) 90 °
DOWN RANGE ERROR
(1 KYD Contour Interval)
(Less than 1 kyd Error)
Depression Angle (β)
20
30
40
-8
-6
-4
-2
0
2
4
6
8
Slope Angle (α)
CROSS RANGE ERROR
(0.5 KYD Contour Inverval)
Depression Angle (β)
20
30
40
-8
-6
-4
-2
0
2
4
6
8
Slope Angle (α)

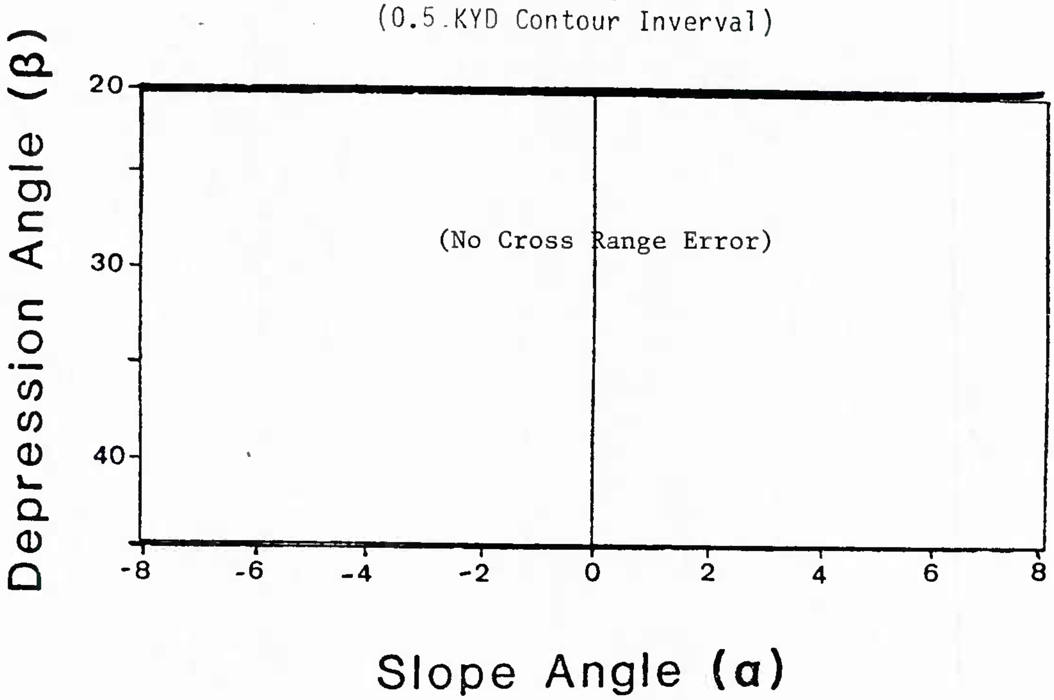
Depth 2500 FM

Cross-slope (θ) 0°

DOWN RANGE ERROR
(1 KYD Contour Interval)



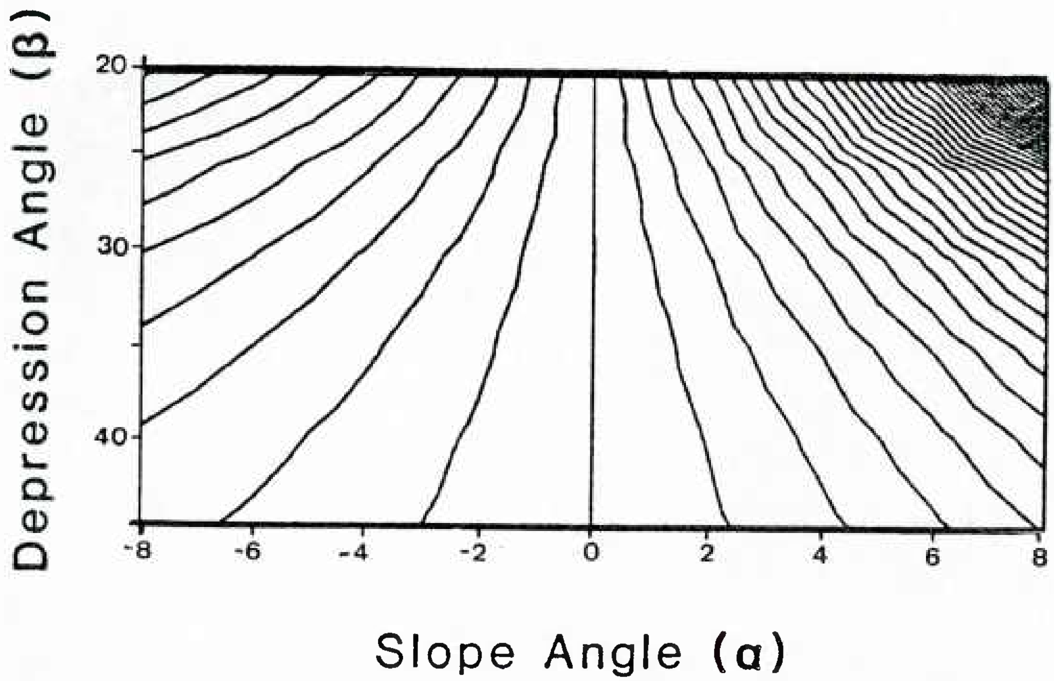
CROSS RANGE ERROR
(0.5 KYD Contour Inverval)



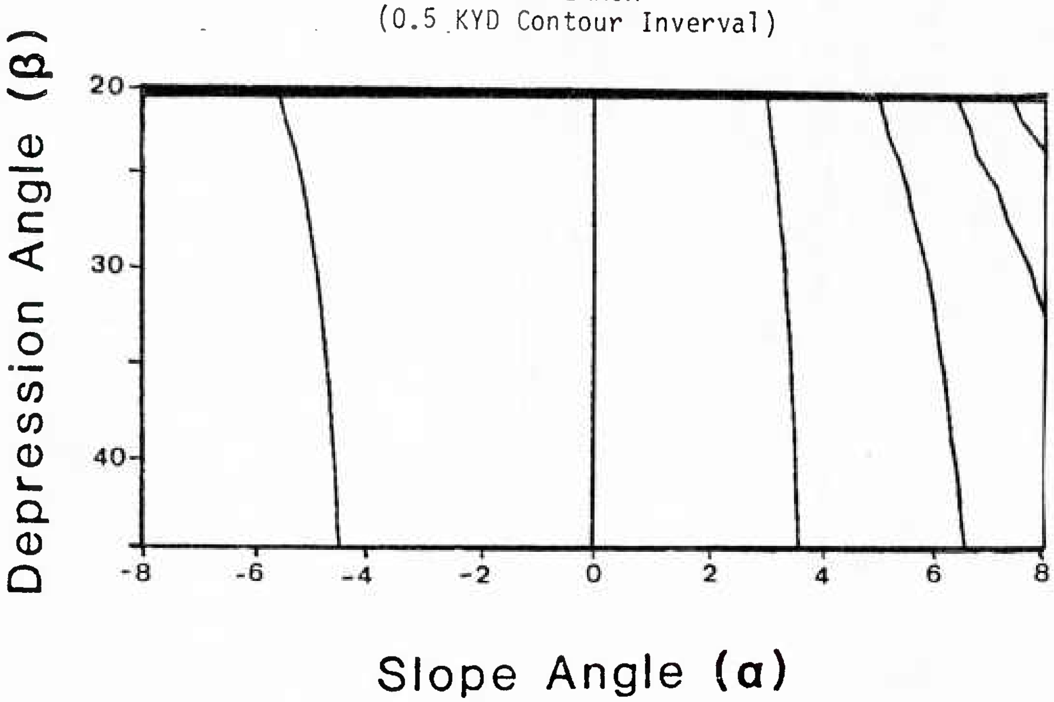
Depth 2500 FM

Cross-slope (θ) 45°

DOWN RANGE ERROR
(1 KYD Contour Interval)



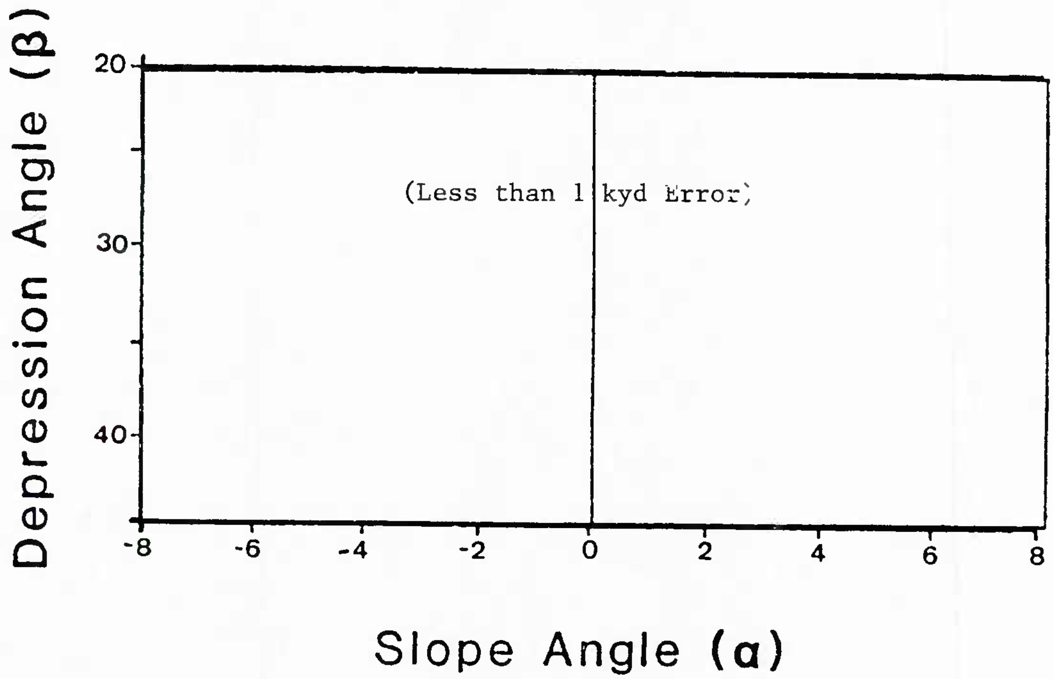
CROSS RANGE ERROR
(0.5 KYD Contour Inverval)



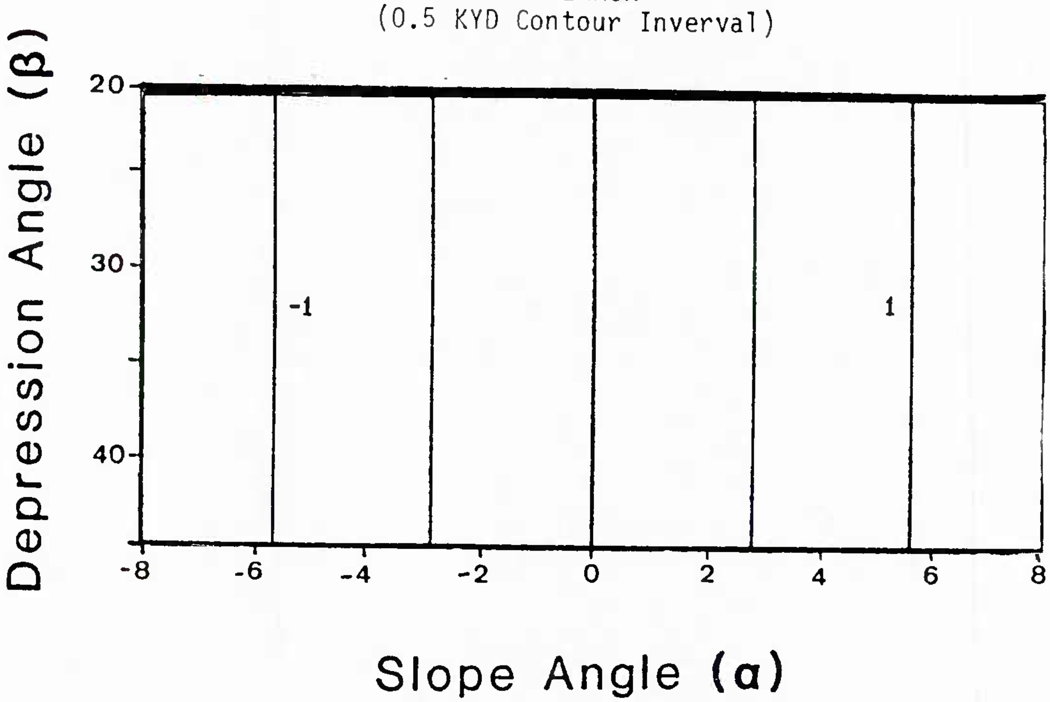
Depth 2500 FM

Cross-slope (θ) 90 °

DOWN RANGE ERROR
(1 KYD Contour Interval)



CROSS RANGE ERROR
(0.5 KYD Contour Inverval)



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Depth and Bottom Slope
J. Matthew Tattersall, 3331
TM No. 831177
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